The PROPEL Electrodynamic Tether Mission and Connecting to the Ionosphere

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***Abstract*—The exponential increase of launch system size—and cost—with delta-*V* makes missions that require large total impulse cost prohibitive. Led by NASA's Marshall Space Flight Center, a team from government, industry, and academia has developed a flight demonstration mission concept of an integrated electrodynamic (ED) tethered satellite system called PROPEL: "*Propulsion using Electrodynamics*". The PROPEL Mission is focused on demonstrating a versatile configuration of an ED tether to overcome the limitations of the rocket equation, enable new classes of missions currently unaffordable or infeasible, and significantly advance the Technology Readiness Level (TRL) to an operational level. We are also focused on establishing a far deeper understanding of critical processes and technologies to be able to scale and improve tether systems in the future. Here, we provide an overview of the proposed PROPEL mission.**

One of the critical processes for efficient ED tether operation is the ability to inject current to and collect current from the ionosphere. Because the PROPEL mission is planned to have both boost and deboost capability using a single tether, the tether current must be capable of flowing in both directions and at levels well over 1 A. Given the greater mobility of electrons over that of ions, this generally requires that both ends of the ED tether system can both collect and emit *electrons*. For example, hollow cathode plasma contactors (HCPCs) generally are viewed as state-of-the-art and high TRL devices; however, for ED tether applications important questions remain of how efficiently they can operate as both electron collectors and emitters. Other technologies will be highlighted that are being investigated as possible alternatives to the HCPC such as Solex that generates a plasma cloud from a solid material (Teflon) and electron emission (only) technologies such as cold-cathode electron field emission or photo-electron beam generation (PEBG) techniques.

***Index Terms*—Electrodynamic Tethers, Spacecraft Charging, Spacecraft–Ionosphere Interaction, Sheath, Electron Emission, Electron Collection, Hollow Cathode**

I. INTRODUCTION

PROPEL is a proposed small spacecraft mission to demonstrate the operation of an electrodynamic (ED) tether propulsion system in low Earth orbit (LEO) over a period of six months. PROPEL has two primary goals: (1) to demonstrate capability of ED tether technology to provide robust and safe, near-propellantless propulsion for orbit-raising, de-orbit, plane change, and station keeping, as well as perform orbital power harvesting and formation flight; and (2) to fully characterize and validate the performance of an integrated ED tether propulsion system, qualifying it for infusion into future multiple satellite platforms and missions with minimum modification.

Of particular importance for efficient ED tether operation is the ability to inject current to and collect current from the ionosphere. ED tether propulsion systems such as PROPEL that must be able to boost and de-boost using a single tether require that tether current can flow in both directions along the tether and at levels well over 1 A. Given the greater mobility of electrons over that of ions, this generally requires that both ends of the ED tether system can both collect and emit electrons.

In this paper, we provide background information on ED tether fundamentals (Section II) and selected historical information of other tether missions (Section III). We then discuss PROPEL's mission goals driving important questions that should be addressed (Section IV) and needed measurements (Section V). These goals also led us to a general-purpose ED tether propulsion design and specific mission objectives (Section VI).

II. ELECTRODYNAMIC TETHER FUNDAMENTALS

As illustrated in Figure II-1, ED tether propulsion generates Lorentz force thrust through the interaction between a current driven along a conducting tether and a planetary magnetic field, using the planet itself as reaction mass rather than an expelled propellant. In general, ED tethers possess three key principles that govern their operation [1]: 1) the conductor has an intrinsic electromotive force (*emf*) generated along it due to the orbital motion of the tether, 2) the conductor provides a low-resistance path connecting different regions of the ionosphere, and 3) access to external electron and ion currents is confined to specific locations, such as the endpoint when the conductor is insulated, or collected along a length of bare tether [2]. We briefly describe these principles below.

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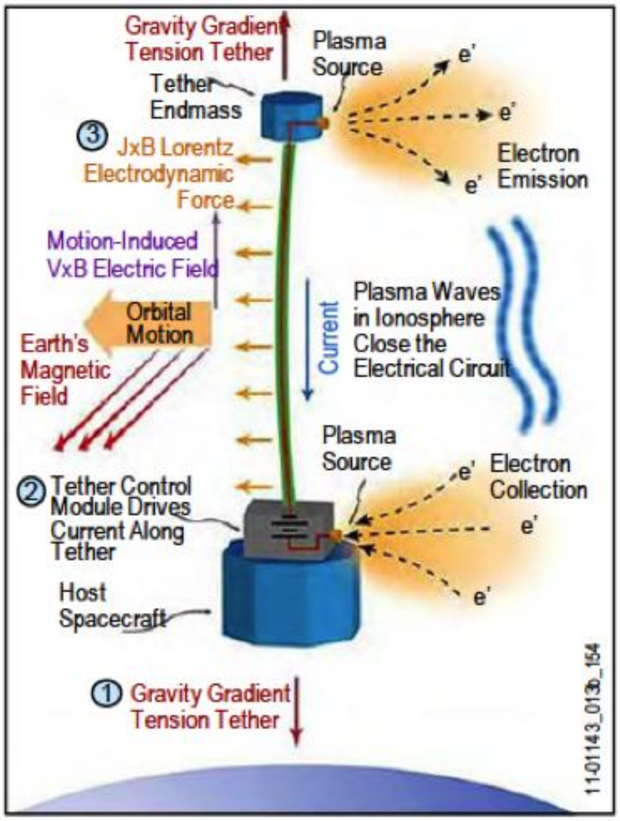


Fig. II-1. The essential physics of ED tether propulsion. An ED tether generates thrust using interaction between current driven along a tether and the magnetic field of the planet it orbits, enabling propulsion without expelling propellant.

The first principle listed above, *emf* generation across the tether, results from the Lorentz force on the electrons in the tether as the system travels through the geomagnetic field. To determine the magnitude of this *emf*, we start with the Lorentz force equation for charged particles:

$$\mathbf{F} = q\left(\mathbf{E} + \mathbf{v}_s \times \mathbf{B}\right), \tag{1}$$

where q is the charge of an electron, $\mathbf{E}$ represents any ambient electric field (small), and $\mathbf{v}_s \times \mathbf{B}$ represents the motional electric field as the host spacecraft travels at a velocity $\mathbf{v}_s$ through the Earth's magnetic field, represented by $\mathbf{B}$. Eq. (1) can be rewritten as

$$\mathbf{F} = q\mathbf{E}_{\mathrm{tot}}, \tag{2}$$

where

$$\mathbf{E}_{\mathrm{tot}} = \mathbf{E} + \mathbf{v}_s \times \mathbf{B}, \tag{3}$$

and represents the total electric field. In order to get the total *emf* generated across the tether, we must integrate $\mathbf{E}_{\mathrm{tot}}$ along the entire length of the tether, l. That is, the total *emf* is

$$\varphi_{\mathrm{tether}} = -\int_0^l \mathbf{E}_{\mathrm{tot}} \cdot d\mathbf{l} \approx -\int_0^l \mathbf{v}_s(l) \times \mathbf{B}(l) \cdot d\mathbf{l}, \tag{4}$$

which is negative since electrons in the tether are acted upon by the Lorentz force. Because the ionospheric plasma surrounding the ED tether system is sufficiently good, the ambient electrostatic field $\mathbf{E}$ is small and is usually ignored, i.e., $\mathbf{E} \approx 0$. The tether potential is path independent assuming a conservative resultant electric field and steady-state conditions. Thus, ϕ_{tether} can be calculated knowing only the relative locations of the endpoints (separation distance and orientation) and does not depend on the position of the tether between the endpoints.

The second and third principles are related to current flow through the tether, which occurs when a connection is made between the tether's endpoints and the surrounding ionospheric plasma. Current closure occurs in the ionosphere, thus making the overall circuit complete. Using Kichhoff's voltage law, the equation for the overall circuit is

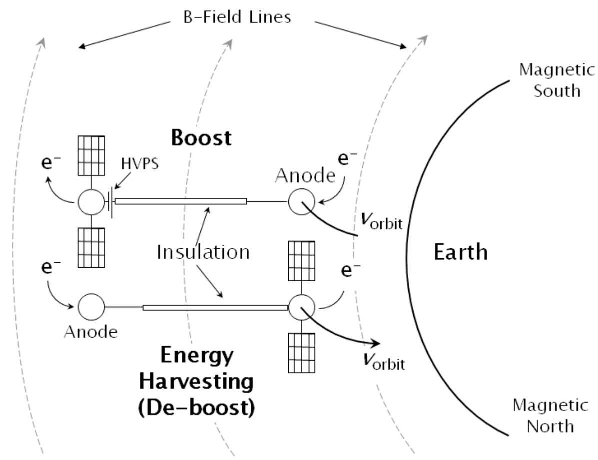


Fig. II-2. ED tethers can be used in an "energy harvesting" mode or a "boost" mode [3].

$$\begin{aligned}\varphi_{\mathrm{tether}} = \; & V_{\mathrm{sat}} + I_{\mathrm{tether}} R_{\mathrm{tether}} \\ & + I_{\mathrm{tether}} R_{\mathrm{load}} + V_{\mathrm{host}} + I_{\mathrm{tether}} Z_{\mathrm{iono}}\end{aligned}, \tag{5}$$

where ϕ_{tether} is the *emf*, V_{sat} is the potential of the endmass satellite with respect to the local plasma, I_{tether} is the current through the tether, R_{tether} is tether resistance, R_{load} is any system load resistance (e.g., resistors, energy harvesters), V_{host} is the potential of the host satellite with respect to the local plasma, and Z_{iono} is the ionospheric effective impedance (~10's of ohms).

The current connection to the surrounding ionospheric plasma can be accomplished via passive or active means. In the passive case, the voltages and currents in the overall system distribute themselves in a self-consistent manner, which can require the endpoints to charge to high levels in order to attract enough current (i.e., V_{sat} and V_{host}). Active means generally employ an electron generator of some type, such as an electron gun or hollow cathode plasma contactor. The advantage of the HCPC is that it has considerable spaceflight heritage and is bi-modal allowing for both electron emission and collection to/from the ionosphere, an advantage of special value for PROPEL which needs reversible current flow. Future ED tether systems may employ alternate approaches to electron emission and/or collection. Some examples are discussed in greater detail in Appendix A. Regardless of the technology used, the need is to make contact with the ambient ionosphere and

exchange currents that satisfies space charge and magnetic field constraints with a low effective impedance. Regardless of the endbody contacting method, current flows through the tether as shown in Fig II-2 for boost and de-boost. For deboost, for example, current flows up the tether because the resultant force on the electrons is downwards. After electrons are collected at the satellite, they are conducted through the tether to the host satellite where they are ejected. Current closure occurs in the ionosphere, thus making the overall circuit complete.

Let us consider the Tethered Satellite System (TSS) system as an example of an upwardly deployed ED tether system in low Earth orbit. That is, the tether is vertically oriented, the Shuttle's orbital velocity, v_{orbit}, is 7.7 km/s in an eastward direction with respect to a stationary Earth ($v_{\mathrm{rot}} \approx 0.4$ km/s), and the geomagnetic field is oriented south to north. Since the ionospheric plasma and geomagnetic field co-rotate with the Earth, the orbital velocity should actually be in the reference frame of the Earth's rotation which yields $v_s \approx 7.3$ km/s, where v_s is the spacecraft velocity relative to the Earth's rotation. Due to the 28.5° orbital inclination, the included angle between the velocity and magnetic vectors varies in a roughly sinusoidal fashion causing the tether potential to vary. With these effects, TSS–1 achieved a peak potential just under −60 V at the 267-m tether length [4]. At the longer 19.7-km deployment of TSS–1R, this potential was close to −3500 V [5]. There were also variations due to tether libration and strength of the magnetic field, which varied depending on the orbital position of TSS.

If current flows in the tether element, a force is generated as given by

$$\mathbf{F} = \int_0^l \mathbf{I}(l) \times \mathbf{B}(l) \cdot d\mathbf{l}\ . \tag{6}$$

In self-powered mode (energy-harvesting or de-orbit mode), this *emf* can be used by the tether system to drive the current through the tether and other electrical loads (e.g., resistors, flywheels, batteries), emit electrons at the emitting end, or collect electrons at the opposite. In boost mode, on-board power supplies must overcome this motional *emf* to drive current in the opposite direction, thus creating a force in the opposite direction (see Figure II-2), thus boosting the system. Thrust levels are highly dependent on applied power and typically less than 1 N.

III. Previous Electrodynamic Tether Missions and Their Results

Space tether technology elements have been demonstrated on orbit over the past 30 years. In this timeframe, there have been over 23 major orbital/suborbital tether missions developed overall. A complete missions list along with their development timeline is presented in Table III-1. Of the nine projects centered on furthering development, engineering, and ED tether technology, eight have had a PROPEL team member in a key role. Moreover, of the 23 identified space tether projects, 12 featured PROPEL team members. These space tether missions typically can be divided into several key demonstration areas (electrodynamics/plasma physics, dynamics, or formation flying). In Figure III-1, the category of tether mission is defined by color; furthermore, the electrodynamics and dynamics projects are in bold color to demonstrate the most relevance in establishing the PROPEL physics and technology.

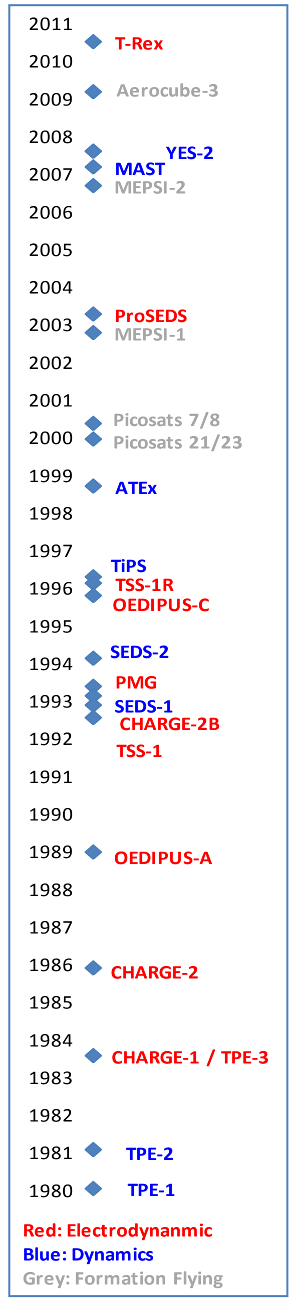


Fig. III-1. Timeline of tether development programs. *The PROPEL team has leveraged tether development programs that stem back to 1980.*

All of the previous missions with which PROPEL team members have been involved, in both technology and mission management roles, are summarized in Table III-1. The figure includes the project name, the mission's relevance to the PROPEL demonstration, the launch date, the tether category and mission summary.

Table III-1. Selected tether missions of relevance to PROPEL. ***The PROPEL team has important connections to each of these missions.***

Project Title and Involved PROPEL Team Members	Relevance to PROPEL	Launch Date	Tether Category and Mission Summary
Tether Experiment (T-Rex)	• Tether deployment • Fast HCPC ignition	31 August 2010	Electrodynamics/plasma physics + Successful deployment of tape and fast ignition of hollow cathode
Multi-Application Survivable Tether (MAST)	• Tether dynamics	17 April 2007	Dynamics + Obtained data on tethered satellite dynamics – Problem with release mechanism resulted in minimal tether deployment
Propulsive Small Expendable Deployer System (ProSEDS)	• Hollow cathode plasma contactor (HCPC), deflection plate analyzer (DPA), and Langmuir probe (LP) instrument development • Measurement device and model development • EDT heritage • Tether development	29 March 2003	Electrodynamics/plasma physics + Model, process, and instrument development – Did not launch because of changed NASA requirements
First Tethered Satellite System Program (TSS-1)	• Tether dynamics • Controlled retrieval • EDT	31 July– 8 Aug1992	Electrodynamics/plasma physics – Too-long bolt added without proper review caused jam in tether deployer + Demonstrated stable dynamics of short tethered system + Demonstrated controlled retrieval of tether
Tether Physics and Survivability Experiment (TiPS)	• Deployment • Long-term survivability	12 May 1996– 20 June 1996 deploy	Dynamics + Successful deployment + Tether survived over 10 years on orbit
Tethered Satellite System Program Relight (TSS-1R)	• Current collection theory • Tether deployment • Plasma potential measurement • EDT	22 February– 9 March 1996	Electrodynamics/plasma physics + Demonstrated electrodynamic efficiency exceeding existing theories + Demonstrated ampere-level current – Flaw in insulation allowed high-voltage arc to cut tether – Tether not tested prior to flight
Small Expendable Deployer System 2 (SEDS-2)	• Deployment and deboost • EDT	9 March 1994	Dynamics + Demonstrated successful, controlled deployment of tether with minimal swing
Plasma Motor Generator (PMG)	• Hollow cathode	26 June 1993	Electrodynamics/plasma physics + Demonstrated electrodynamic boost and generator mode operation – Did not measure thrust
Small Expendable Deployer System 1 (SEDS-1)	• Deployment and deboost	29 March1993	Momentum exchange + Demonstrated successful, stable deployment of tether + Demonstrated controlled deorbit of payload
CHARGE-2B	• High-voltage operations	29 March 1992	Electrodynamics/plasma physics + Full deployment of conductive tether + Demonstration of active electron emission + Demonstrated hollow cathode-like neutralizer
CHARGE-2	• High-voltage operations	14 December 1985	Electrodynamics/plasma physics + Full deployment of conductive tether + Demonstration of active electron emission + Demonstrated hollow cathode-like neutralization

IV. Important Electrodynamic Tether Questions to Advance Technology

While fundamental aspects of ED tether performance have been demonstrated during previous ED tether missions, there are important questions that deserve greater investigation for certain applications. Specifically, PROPEL is intended to advance the TRL for a propulsion system that can support a broad range of capabilities, e.g. boost, deboost, inclination change, drag make-up, and energy harvesting. This is in contrast to a system with more focused goals, e.g. just deorbit or drag make-up. This requires a system architecture that has an appropriate level of symmetry to enable current flow in both directions (boost and deboost) as suggested in Fig. II-1. For that configuration and to achieve the mission goals for PROPEL as outlined in Section I, we have identified several key questions pertaining to tether electrodynamics to be addressed during the PROPEL mission as discussed below. We note that there are also equally important tether dynamics questions, not discussed here, that must be considered to fully advance the TRL level of an ED tether system.

A. Electrodynamics

1) Predicting hollow-cathode plasma contactor performance

To enable bi-directional tether current flow, the PROPEL mission will use hollow-cathode plasma contactor (HCPC) devices placed at each end of the tether with one emitting electron current and the other collecting electron current. We thus need to adequately understand HCPC performance in the ionosphere and ask: **What is the predictable performance of a hollow-cathode plasma contactor (HCPC) to collect current from and emit current to the surrounding ionosphere in terms of tether current, HCPC parameters, and ionospheric conditions?** The motivation for establishing a clear answer to this question is motivated by our present understanding of HCPC operation in the ionosphere.

Over at least the last 25 years, there have been numerous studies and ground chamber tests of HCPCs for high current performance in both electron collection and emission modes [6, 7]. What is missing is definitive, in-space, high-current HCPC experiments to clarify actual performance in connecting current flow between the ED tether and the ionosphere. We focus on the electron collection process as it is generally believed to represent the largest effective impedance (as compared to electron emission). We cite two theoretical models to highlight the uncertainty [8]. These models are thought to represent upper and lower bounds of electron-collection performance. The first was developed by Katz *et al.* [9] and implemented in the NASA Environment Workbench (EWB) [10]. It assumes that the HCPC's plasma plume expands roughly spherically as a highly turbulent, quasi-neutral cloud that provides a slow-moving ion current emitted by the HCPC which neutralizes the high-speed incoming electron current space charge. The plume has an effective radius determined when the effective scattering frequency of the plume plasma is equal to some fraction of the electron gyrofrequency. The collected electron current is essentially limited to the electron thermal current across the spherical double layer of the plume, as illustrated conceptually in Figure IV-1.A (The double layer serves as the interface between two plasma populations.) The second, proposed by Gerver *et al.* [11], models the plasma plume as expanding roughly cylindrically along the geomagnetic field lines, as illustrated in Figure IV-1.B. It assumes that electrons are collected by collisional transport across magnetic field lines and via a double layer at both ends of the plume. Because of the differences of geometries between the two models, the Gerver *et al.* [11] model tends to predict higher collected electron current for a given emitted ion current level, HCPC bias voltage, and ionospheric condition.

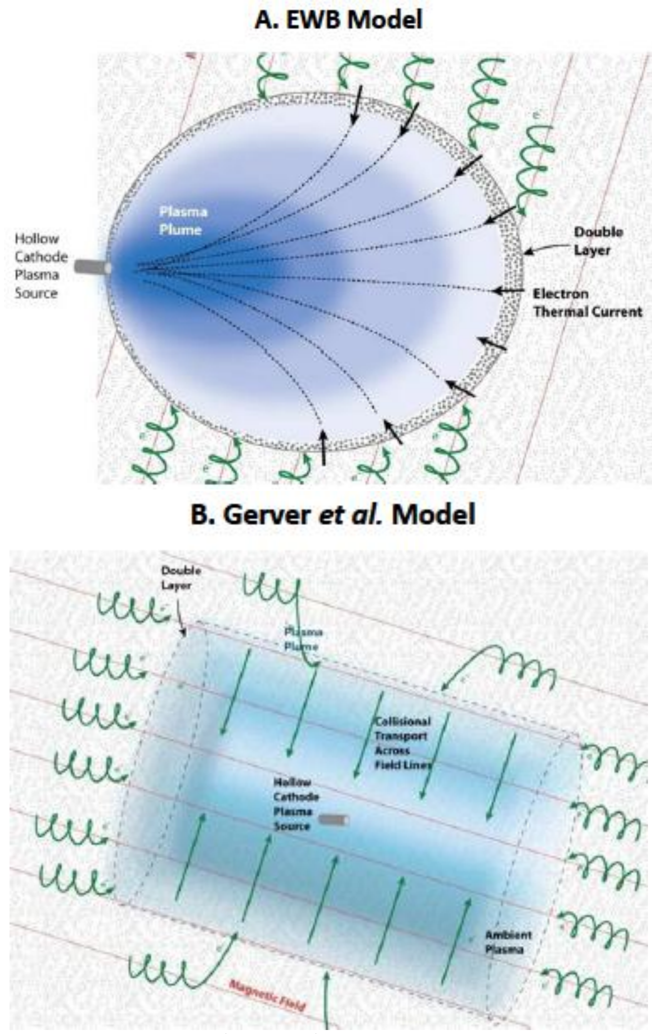


Fig. IV-1. Comparison of models of electron collection by HCPCs. (a) The EWB HCPC model [10] (b) Gerver *et al.* model. [11]

2) Performance as a function of increasing tether current

The TSS-1R mission demonstrated an ability to draw currents that reached just over 1 A in a system where the tether may have been the dominant impedance element in the overall tether circuit [12]. However, for propulsion applications, the tether impedance will be much lower and tether currents of several amps or more will be required. We thus ask: **How does ED tether performance change with increasing current (above 1 A) and how can the tether system be optimized for high current operation?**

For low power applications (such as the PMG mission), the tether end bodies operate in the thermal current regime. Prior to the TSS missions, this regime was thought to be adequately described by the Parker–Murphy (PM) model [13]. However, TSS measurements found PM current collections predictions to

be too low by a factor of 2–3. An *ad hoc* modification to the PM model agrees with the TSS data but, since the exact physical mechanism is still unknown, the *ad hoc* correction may not hold under more general, and higher current, conditions.

When current is pushed above the level that can be provided by thermal currents at the plume double-layer boundary, tether endbody potential relative to the ambient ionosphere must increase more rapidly (increasing impedance). It is possible in this situation for additional plasma to also be generated by ionization of (un-ionized) gas from the HCPC, spacecraft out-gassing or sputter products, or ambient neutrals (in LEO, neutrals are ~1000× denser than electrons). It is critical to determine the amount and source of any anomalous ionization. No ED tether has ever operated in this regime. PROPEL will operate in both the lower power regime described above as well as this higher power regime. Correspondingly, if ED tethers are to be used for more ambitious missions where higher thrust and power are required (e.g., Hubble, ISS reboost, or a MXER facility), then it is essential that this regime be explored.

B. ED Tether Operations

It is not unreasonable to compare ED tether maneuvering (e.g., boost, deboost, inclination change, drag make-up) to sailing a boat. With a sail, one can only go where and how the wind and currents allow! Similarly, for an ED tether, it only can be maneuvered where and how the planetary magnetic field, ionosphere, and atmosphere allow. Predictable flight operations, i.e. getting from Point A to Point B will therefore depend on an appropriate level of space weather forecasting, real-time observations, performance prediction, and integrated simulation. A general maneuvering strategy likely will depend initially on larger, less precise maneuvers followed by smaller, more precise maneuvers. Thus, with the PROPEL mission we will seek to answer: **What level of forecasting, real-time observation, performance prediction, and integrated simulation are required to enable safe ED tether system maneuvering?**

V. PROPEL Electrodynamic Measurement Goals

Here, we focus on the needed measurements to properly address the questions pertaining to the tether electrodynamics identified in Section IV. As noted there, to raise the TRL of an ED tether *system* we must also address dynamic and physical attributes of the tether system that are not discussed here.

In terms of understanding the electrodynamic state of the system (e.g., tether current, HCPC plasma plume, electrodynamic force, etc.) we can divide measurements into two groups: (1) those that measure the internal parameters of the (hard-wire) electrical circuit (e.g., the current flow in, and voltage drop across the tether) and (2) those that determine the external leg of the circuit (e.g., the voltage drop and current flow between each tether end and the surrounding ambient ionosphere (magneto-plasma)). As in any electrical circuit loop, current flow in the tether depends on the characteristics of the whole tether series circuit—including the distributed, external return current leg that connects with the ionosphere. Here, we focus on the "electrodynamic" measurements that address the external leg of the circuit with the following measurement categories:

Characterization of ambient ionosphere. Understanding the ambient environment is essential to establishing the local plasma parameters around the tether ends where current collection and emission take place. The most spatially and temporally variable parameters will be ionosphere plasma density (charge neutrality assumed) and electron temperature. In general, while understanding the neutral atmosphere make-up and density, as well as the ambient magnetic field, is essential, this information can be obtained via models. For tether lengths of several to ten or so kilometers, knowledge of ambient conditions at one end is adequate for understanding the environment at both ends, at least for quiet conditions. Concerns for strong vertical gradients, for example due to equatorial plasma bubbles, may require ambient measurements at both ends.

Characterization of current flow at tether collecting/emitting ends. In the presence of HCPC dense plasma plume emissions (which includes un-ionized gas from the HCPC), the environment around both tether ends is highly disturbed. The effective impedance between the ionosphere and the tether endbodies is also expected to be nonlinear as a function of tether current. Quantifying the HCPC plume, how it interacts with the ambient ionosphere, and identifying possible anomalous ionization effects under varying conditions will all be valuable information. This disturbed (non-Maxwellian) plasma environment will be highly localized and will have complex flow depending on source locations, magnetic field direction, and spacecraft velocity direction. Under this situation, knowledge of plasma density, electron and ion velocity distribution, potentials with respect to the spacecraft and ambient plasma, and neutral density composition are required for a complete assessment of the state and processes at both tether ends.

To properly understand the ambient and disturbed plasma states at the tether ends a combination of surface mounted and boom-mounted sensors will provide the necessary measurements. Figure VI-2 shows a boom placed on both tether spacecraft end-bodies. The boom is intended to provide a position that provides a direct measure of the ambient ionosphere and also "looks" both out and inward towards the spacecraft. Combined with spacecraft surface-mounted sensors that look out, a more complete picture of the complex interactions at both tether ends should be possible.

VI. PROPEL Mission Description

PROPEL was designed with multiple end users in mind. To this end, the design team defined a set of mission objectives, detailed in Table VI-1, to establish ED tether propulsion ready for operational use.

PROPEL's Design Reference Mission (DRM) operational profile (Figure VI-1) is designed to demonstrate the necessary ED tether operational readiness objectives during its 6 month mission life. PROPEL's multi-step demonstration approach provides operational capability data in a characterized plasma environment to validate operational ED tether propulsive systems immediately after commissioning.

DRM Phases 1–3: PROPEL launches into a 500-km circular orbit. This altitude provides very good environmental plasma conditions for the demonstration (e.g. ionospheric

plasma electrical conductivity). A 500-km insertion also allows for a complete system checkout and tether deployment at an altitude above the International Space Station (ISS) orbit, and provides for a slow passive decay in case of an operational anomaly. Tether deployment will be initiated after solar array deployment, host spacecraft (HS) and end mass (EM) checkout, instrument boom deployment, and HS/EM separation.

Table VI-1 PROPEL will demonstrate capabilities that will enable new missions.

PROPEL Objective	Capability Enabled
System-level demonstration of ED tether propulsion delivering high thrust-to-power and large total impulse for LEO maneuvering and station keeping	• Low-mass systems to produce large ΔV, reducing launch vehicle size and total life-cycle costs for many future missions • Highly efficient orbital maneuvering and plane change of LEO spacecraft • Long-duration, low-LEO drag makeup of large space systems
Accurately predict, verify, and control ED tether orbital maneuvering, and validate simulation and modeling tools	• Multiple precise orbital maneuvers and rendezvous with small, affordable systems • Long duration precision station keeping • Predictive control ensures flight safety
Demonstrate orbital energy harvesting	• High burst power with lower mass and cost • Power generation at the outer planets without RTGs
Validate survival and operation of a conducting tether for an extended period	• Tether performance data over a long mission duration will enable extrapolation to extended periods

DRM Phases 4–13: PROPEL will demonstrate full ED tether propulsive capabilities by raising the orbit from 500 km to 650 km after tether deployment and initial characterization. Diagnostic instruments are mounted on each end-body and allow the propulsive performance to be correlated with the surrounding space plasma environment. Following validation, the existing analytic performance models will be used to predict ED tether performance to support mission operations. Subsequent mission phases include deboost/power generation, inclination change, precision orbital maneuvering, drag make-up, and deorbit.

Figure VI-2 illustrates the PROPEL system architecture. The PROPEL space vehicle consists of the Host Side (HS) spacecraft and Endmass (EM) spacecraft separated by a 3-km tether with the HS at the lower altitude. The ED tether propulsion hardware consists of a 3-km conducting, multi-string tether with a tether deployer on each end body. The reel-type deployer has deployment and retrieval operational flight heritage with the two Tethered Satellite System (TSS) missions. A Hollow Cathode Plasma Contactor (HCPC) on the host and end mass is used for electrical contact with the ionosphere.

PROPEL tether deployment will be monitored by on-board cameras, accelerometers, and tensiometers. The tether and deployment system also includes cutters and dual retractors on each side to enhance system safety in the event of a severed tether. The tether diagnostic hardware will provide tether dynamics, electrodynamic performance, and natural ionospheric and PROPEL-induced plasma environments measurements. Measurement correlations will validate existing theoretical models and allow us to extrapolate performance to a broad range of space conditions and applications. The Langmuir probe provides reliable electron data at the boom tip. The hemispherical RPA offers a wide angle integrated ion flux measurement. To determine ion energy and density requires angle-of-incidence information provided by the Deflection Plate Analyzer (DPA).

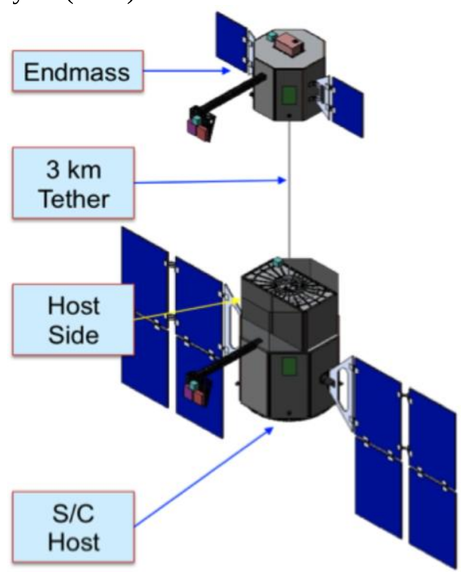
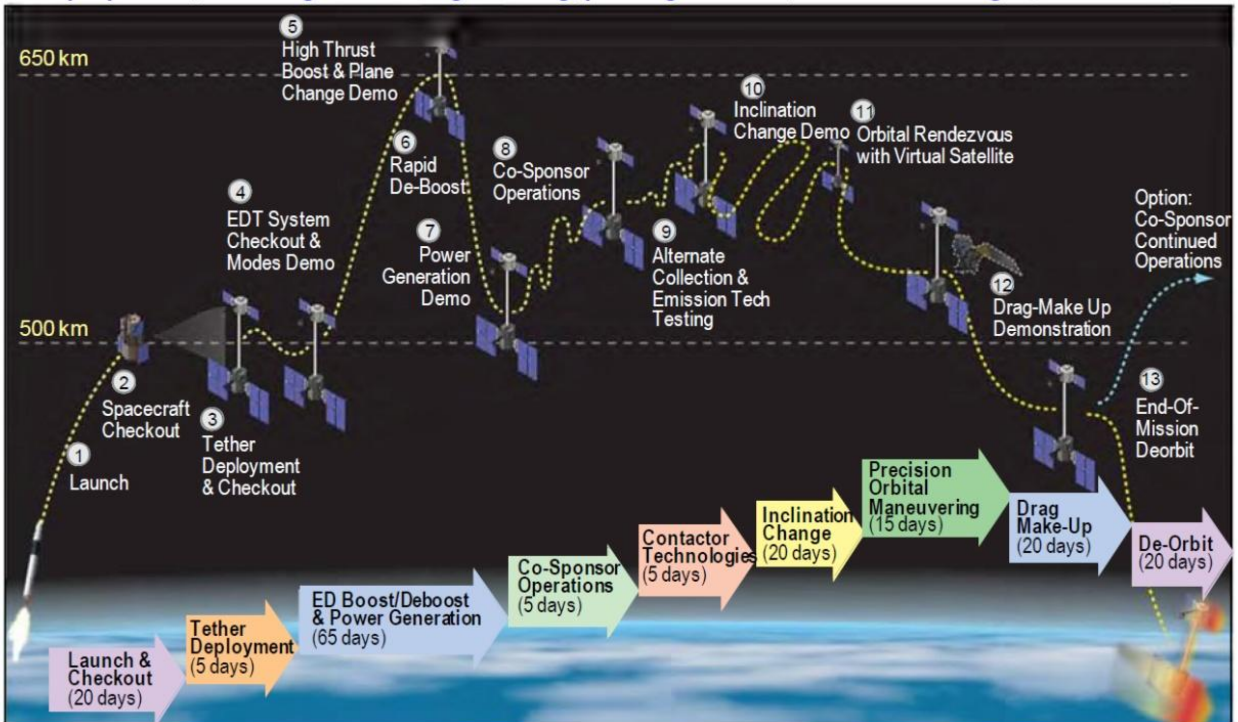


Fig. VI-2 The PROPEL consists of two spacecraft connected by a 3-km conducting tether.

VII. Conclusion—Looking to the Future of Electrodynamic Tethers

The PROPEL mission represents a significant effort to advance the TRL of ED tether technology to an operational level. While the focus of this paper is principally on the "electrodynamics" of the system, the PROPEL mission itself addresses all aspects of an operational system, including dynamics, reliability, safety, operational planning, and external coordination. The PROPEL ED tether is being configured to validate operations associated with boost, deboost, inclination change, drag make-up, energy harvesting, and deorbit.

The mission is being designed to quantify electrodynamic performance over a wide range of ambient conditions and thrust (tether current) levels. This includes specialized instrumentation to explore the connection between tether end-body spacecraft and the ambient ionosphere.



Mission Event Description			
1	Rideshare launch to 500 km circular orbit	8	Dedicated co-sponsor operations (restricted)
2	Host and End Mass checkout prior to separation and tether deployment	9	Alternate collector/emitter demos (SEP & EFED; zero propellant ΔV)
3	Controlled tether release and deployment	10	Inclination change demonstration (> 0.1 deg)
4	Diagnostics on ED tether and plasma environment, SV attitude control	11	Autonomous trajectory profiling and rendezvous (<10 km)
5	Orbit raising using (>100 km; max ΔV characterization)	12	Orbit maintenance in high drag environment (<300 km)
6 & 7	Orbit lowering (>100 km) and power generator mode (>250 W)	13	Final de-orbit or transfer to co-sponsor for continued ops

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Fig. VI-1. PROPEL's 6-month operation life will demonstrate all aspects of ED tether propulsion and power generation capabilities in LEO.

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APPENDIX A – ALTERNATE CONTACTING TECHNOLOGIES

As noted above, the advantage of the HCPC is that it has considerable spaceflight heritage and is bi-modal allowing for both electron emission and electron collection to/from the ionosphere. With its dense, extended plasma plume and sheath area it is able to make contact with the ionosphere at lower space-charge current levels than say, a highly confined electron beam (for electron emission) or a large physical collecting surface area (passive electron collection). In addition, an HCPC must deal with the complication of a pressure tank and the lifetime limit of using an expendable gas (typically xenon). Here, we highlight three alternate technologies that support either electron collection, emission, or both.

A. Solid Expellant Plasma Generator

The Solid Expellant (SOLEX) plasma generator is capable of emitting currents an order of magnitude greater than state-of-the-art devices. It is based on a phenomenon observed in the tether-break event that occurred during the Tethered Satellite Reflight (TSS-1R) mission. Prior to the tether breaking at the Shuttle, the tether was deployed to 19.7 km and was carrying 1 A of current. Surprisingly, the current (measured at the satellite) *remained* at 1 A for 75 seconds *after* the break. Subsequent research has shown that the current was most likely maintained by an electrical discharge into the ionospheric plasma—powered by the tether's 3400-V motional *emf* and fueled by Teflon insulation that was vaporized by the heat of the discharge [A1].

ManTech/NeXolve (formally SRS Tech-nologies) has investigated this phenomenon in an effort to develop it into a useful plasma generator that is based on a phenomenon that, because of the TSS-R tether-break event, is known to work in space [Stone, 2005]. The primary limitations that had to be overcome were the corrosive vapor products of Teflon (hydrogen fluoride) and discharge stability. In addition, a useful plasma generator would require a long operational life and a high-current discharge (well above one amp) at low voltages. Teflon was replaced a hydrocarbon material to eliminate corrosive vapors, and the electrode and expellant block were designed to provide a stable discharge and long life. The design resulted in a high voltage discharge, such as that shown in Figure A-1, which ranged to up to several amps, operated stably and restarted reliably.

The SOLEX is a promising high-current plasma source that is simple and robust (having no moving parts, pressure vessel, plumbing, or valves). Its small size and mass, high-current, low-voltage discharge capability, insensitivity to contamination, reliable restart, and the fact that it requires no power for stand-by or pre-conditioning makes it suitable to a variety of applications such as plasma contactors for electrodynamic tethers, spacecraft charging control, and electric propulsion.

Fig. A-1 SOLEX being chamber tested at 1.8 A.

B. PhotoElectron Beam Generator (PEBG)

The PhotoElectron Beam Generator (PEBG) is a new collimated electron source under development at NASA MSFC for spaceflight applications, and potentially of use as an ED tether electron source. Recent advances in light emitting diodes (LEDs), both in higher optical intensities and shorter

wavelengths, have provided key enabling technologies for this new electron source. These advanced LEDs, ranging from short blue ($\lambda \approx 450$ nm) to near ultraviolet ($\lambda \approx 260$ nm), are used to photoeject electrons off a target material, and these photoelectrons are subsequently focused into a laminar beam using electrostatic lenses. Electron energy is controlled by the voltage on the lenses, whereas the electron flux is controlled by the brightness of the LEDs. Key features include low source voltage (±5 V regulated), long lifetime (~100,000 hours), temperature independence over the range from -30° C to +55° C, and the ability to decouple beam intensity from beam energy. Particle trajectory modeling shows that with a single set of lenses, the cathode can produce a laminar beam with an energy range from 0.4 eV to 30 keV. The acceleration voltage of the instrument is set by the upper limit of the desired energy range. Electron beam currents of 0.1 mA have been demonstrated in the lab with just three of the 260-nm LEDs, confirming theoretical calculations for the magnitude and illustrating an effective quantum efficiency of 80%. The target material is lanthanum hexaboride, LaB_6, which has a work function of 2.5 eV. With the incorporation of super-bright blue LEDs, we anticipate an effective electron beam current of at least 1.0 A with a 12-LED source. The LEDs are delivered with focusing lenses to ensure that the entire light beam is concentrated on the target. For the purposes of ED tether current control, the photoelectron gun can be designed to operate in two modes: high-voltage and low-voltage.

The PEBG works by illuminating a target material and steering photoelectrons into a laminar beam using electrostatic lenses (Figure A-2). Figure A-3 shows assembled and exploded views of the basic prototype structure of the PEBG. The instrument consists of a base assembly (housing one electronics board), a target disc that serves as the electron emitting plate, an inner electrostatic lens, a connection board to provide connections to the LEDs, an outer case, and an aperture endcap with a guard ring. A Teflon insert electrically isolates the inner lens from the case and aperture endcap. The lens has its own endcap welded to the cylinder with an aperture in the center surrounded by six sockets arranged in a concentric ring. One LED fits snuggly into each of the six sockets and is oriented toward the emitter plate. The emitter plate is biased negatively with respect to the case (usually at vehicle common), and the inner lens is fixed at a potential that is a fraction of the negative voltage placed on the emitter plate. This voltage configuration eliminates the need for an external lens to produce a laminar beam, demonstrated with computer simulations for beam energies from 0.4 eV through 30 keV. The beam energy is then controlled by the voltage on the two biased electrodes, whereas the flux is controlled by the brightness of the LED source.

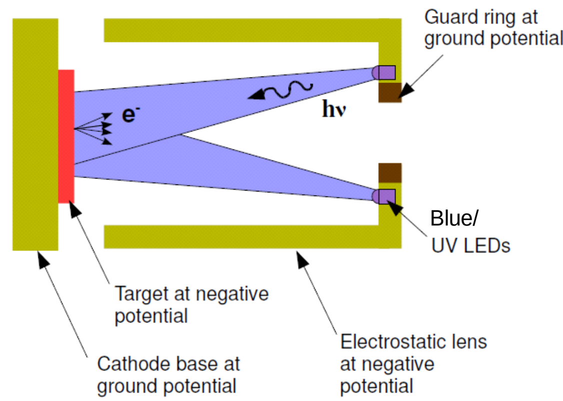

Figure A-2. LEDs illuminate a target to photoeject electrons, then accelerated with electrostatic lenses.

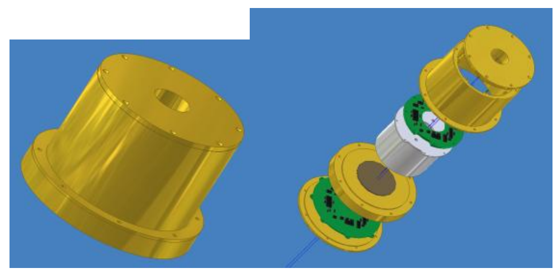

Figure A-3. Assembled (left) and exploded (right) views of the PEBG.

Model calculations were performed to ascertain the relationship between electrode voltages and beam energy, information critical for the design of the electronics. Results are shown in Figure A-4. The upper panel shows the evolution of a sample electron's energy as it propagates along the beam axis. For an emitter plate voltage of −5 V, a cylinder voltage of −4 V, and a guard ring at chamber ground, the resulting beam energy is 2.8 eV. Note that the beam energy is relatively uniform beyond 5 cm from the emitter plate. The laminar flow and the uniform beam energy make this simple electrode configuration an attractive design.

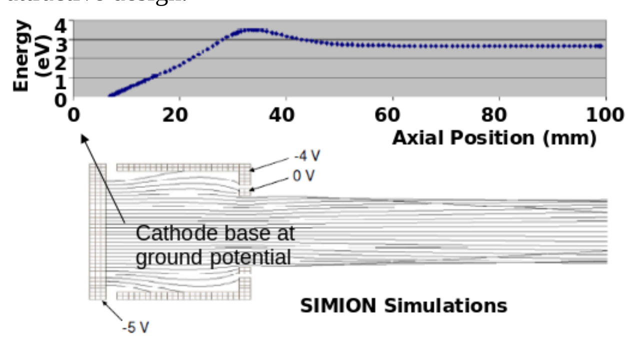

Figure A-4. SIMION simulations show a laminar, monoenergetic electron beam for a −5 V target and a −4 V lens configuration, resulting in a 2.8 eV electron beam. Simulations have shown laminar beams for energies from 0.4 eV to 30 keV with one set of lenses.

C. *Electron Field Emission Array Cathodes*

We also note continued interest in a wide variety of “cold cathode” field emission concepts that draw electrons out of the conduction band of a conducting material due to strong electric fields. The principal reason for considering cold cathode

concepts for electron emission, beyond the possibility for eliminating a consumable, is the potential to utilize sufficiently large emission areas that reduce space charge effects without excessive DC power heaters and acceleration [A2, A3] REF Morris, Gilchrist MRS 2000]. We highlight several here.

"Spindt-Style" Field Emitter Arrays (FEA) – Typical "Spindt style" field emitter arrays employ molybdenum or silicon tips fabricated by ion etching techniques [A4]. Emitters can have a radius of curvature of a few tens of angstroms [A5] with packing densities on the order of 10^6 tips/cm^2 [A6]. Tip electric fields must be on the order of 10^9 V/m for good emission. Field emission currents per tip of 10 µA can be achieved routinely but can be as high as 50 µA if transition metal carbides (TMCs) are run in a pulsed mode. At high packing densities, low current-per-tip values nevertheless result in technologically impressive current densities of greater than 2000 A/cm^2 [A7, A8] the highest current density achieved by any emitter technology (cold cathode or thermionic). For example, an MIT array with a packing density of 10^9 tips/cm^2 produced 2460 A/cm^2 even though the current was a modest 2.5 µA/tip [A9]. Figure A-5 shows an example photo of such a device.

Surface contamination is a critical concern because of its impact to the work function of the surface as well as its contribution to arcing. Protective enclosures, electron cleaning, androbust coatings are part of the solutions [A10-14]. In addition, arc suppression to improve robustness in an outgassing environment has been proposed [A15-16].

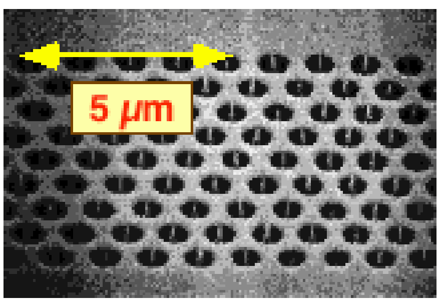

Figure A-5. SEM photograph of SRI Ring Cathode developed for the ARPA/NRL/NASA Vacuum Microelectronics Initiative (emission gated rf amplifier), courtesy of Capp Spindt. These arrays were not resistively protected nor coated, but nevertheless produced 0.67 µA/tip @ a gate voltage of 70 V in a power tube (klystrode) environment.

Carbon Nanotube Emitters. The use of carbon nanotube structures for electron field emission is receiving considerable attention because of their thin diameters, high high aspect ratio (length-to-width), good conductivity, and possible resliance to atomic oxygen [A17, A18].

Ion Proportional Surface Emission Cathode (IProSEC). IProSEC is a novel concept for applications where large surface areas can be made available for electron emission. As such it is described as a low-brightness device by concentrating an electric field between a p-doped insulating substrate based on a high angle cut of the substrate at the boundary with an adjacent metal cathode element. The substrate is held positive of the cathode to enable the strong electric fields [A19].

Low Work-Function Coated Tether—. A recent publication has described the idea of coating the cathodic end of a bare ED tether with an extremely low work function material: calcium aluminate electride (12CaO • 7AL_2O_3 (C12A7)). It has a reported work function as low as 0.6 eV because of a unique nanocrystalline lattice structure. This allows the consideration of a near room-temperature emission current density profile achieving over 100 µA/mm^2 [A20].

The PROPEL Electrodynamic Tether Mission and Connecting to the Ionosphere

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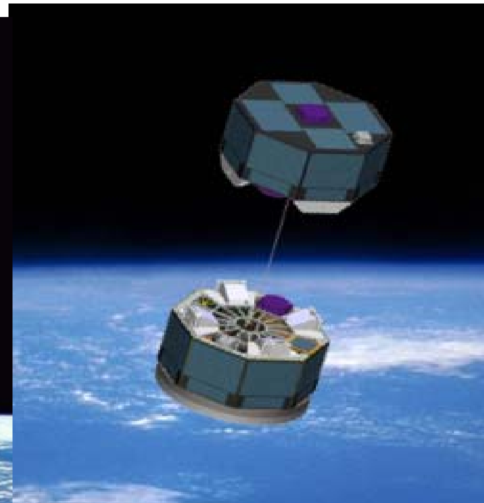
**Propel PI

Outline

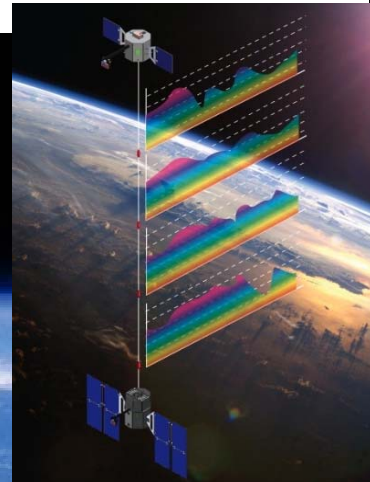
- **Electrodynamic (ED) Tether Propulsion Basics**
- **ED Tether TRL**
- **PROPEL & Design**
  - Mission Goals
  - Current Collection/Emission
  - Configuration
- **Possible future electron emitter / collector technologies**

Missions and Applications Enabled by *EDT Propulsion*

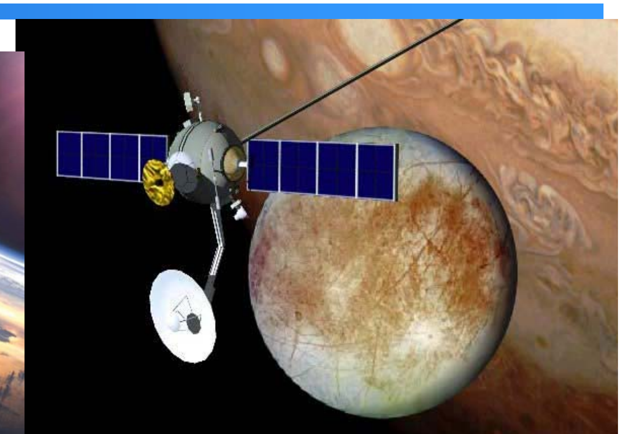
Orbit Transfer Vehicle
(small to large s/c)
boost/deboost/inclination



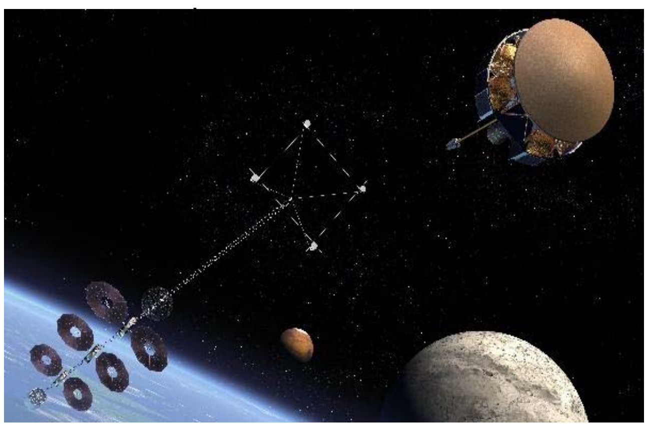
Formation Flying



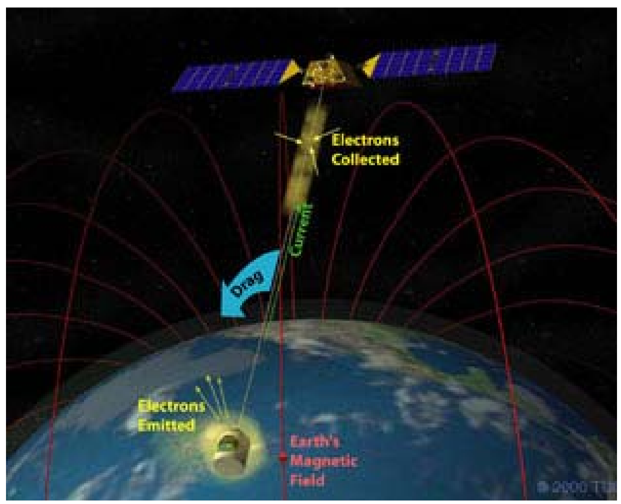
Multipoint Ionospheric Science



Up to 1 MW Power Generation & Propulsion at Gas Giants

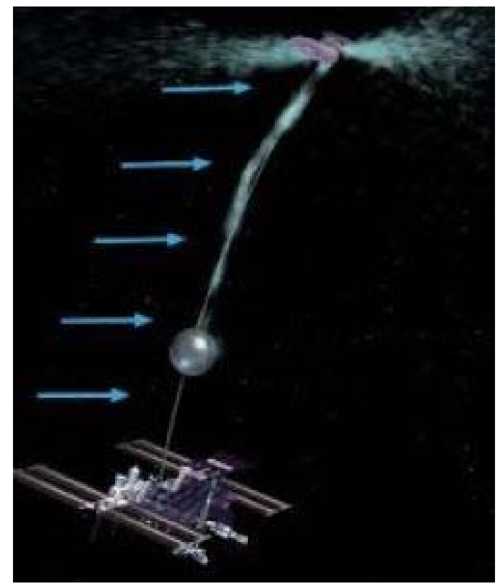


Reusable Launch Assist and LEO-to-GTO Transfers



End-Of-Life Deorbit and Active Orbital Debris Removal

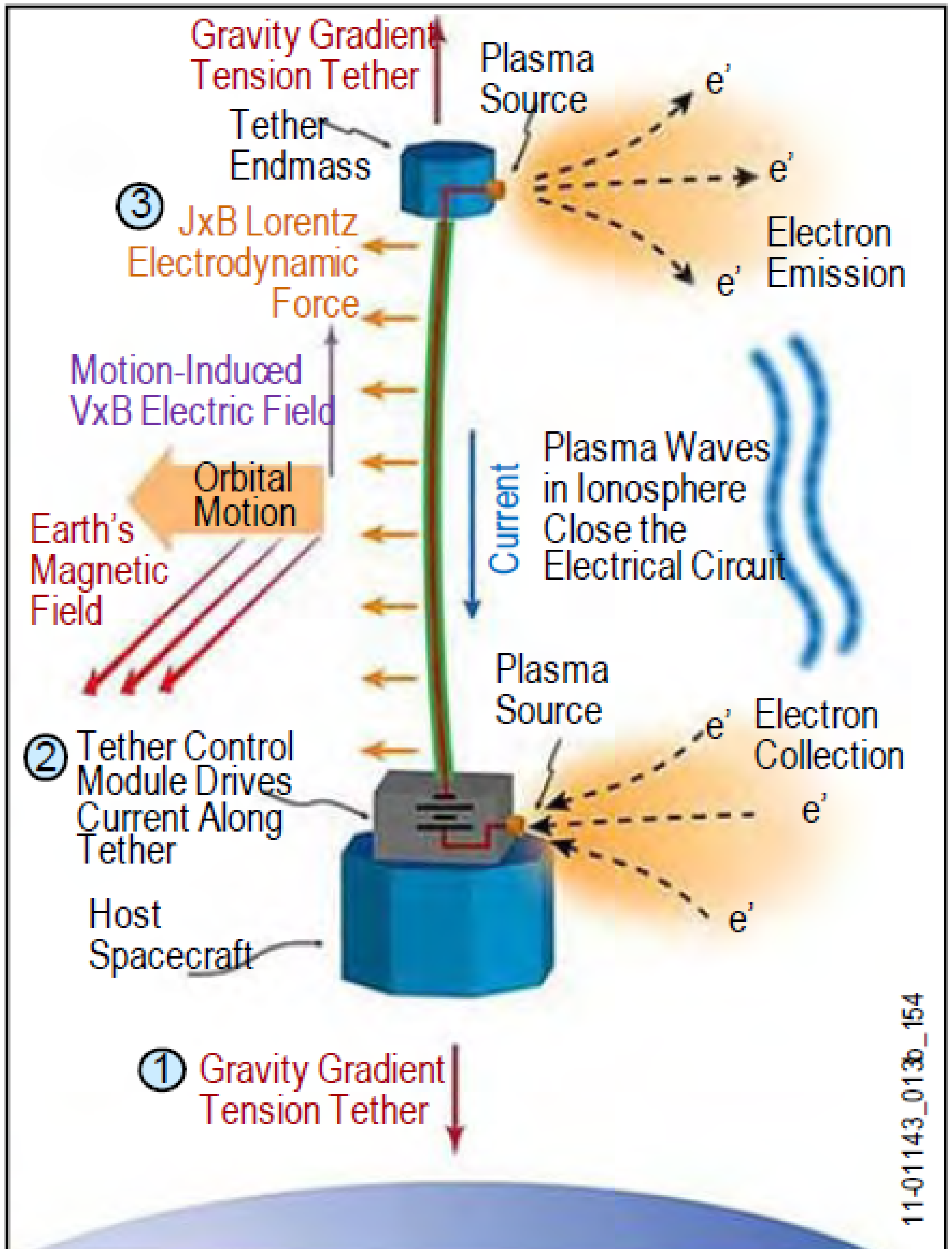
3



Reboost of Large Space Platforms

EDT Propulsion Fundamentals

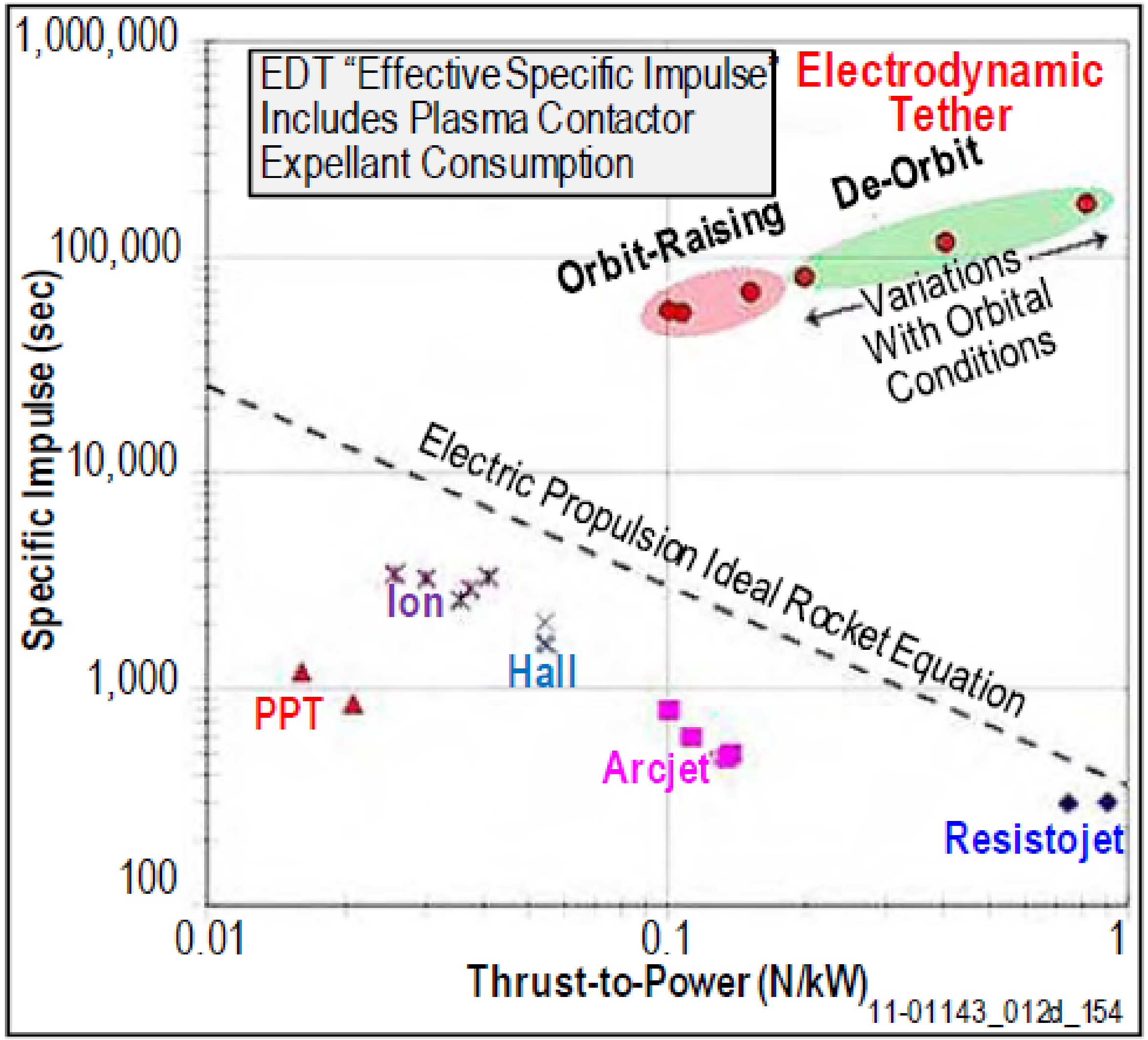
- **Electrodynamic tethers generate thrust between tether current and magnetic field of planet**
- ***Propellantless Propulsion* possible.**
  - HCPCs limit to low consumable scenario



EDT vs. Electric Propulsion

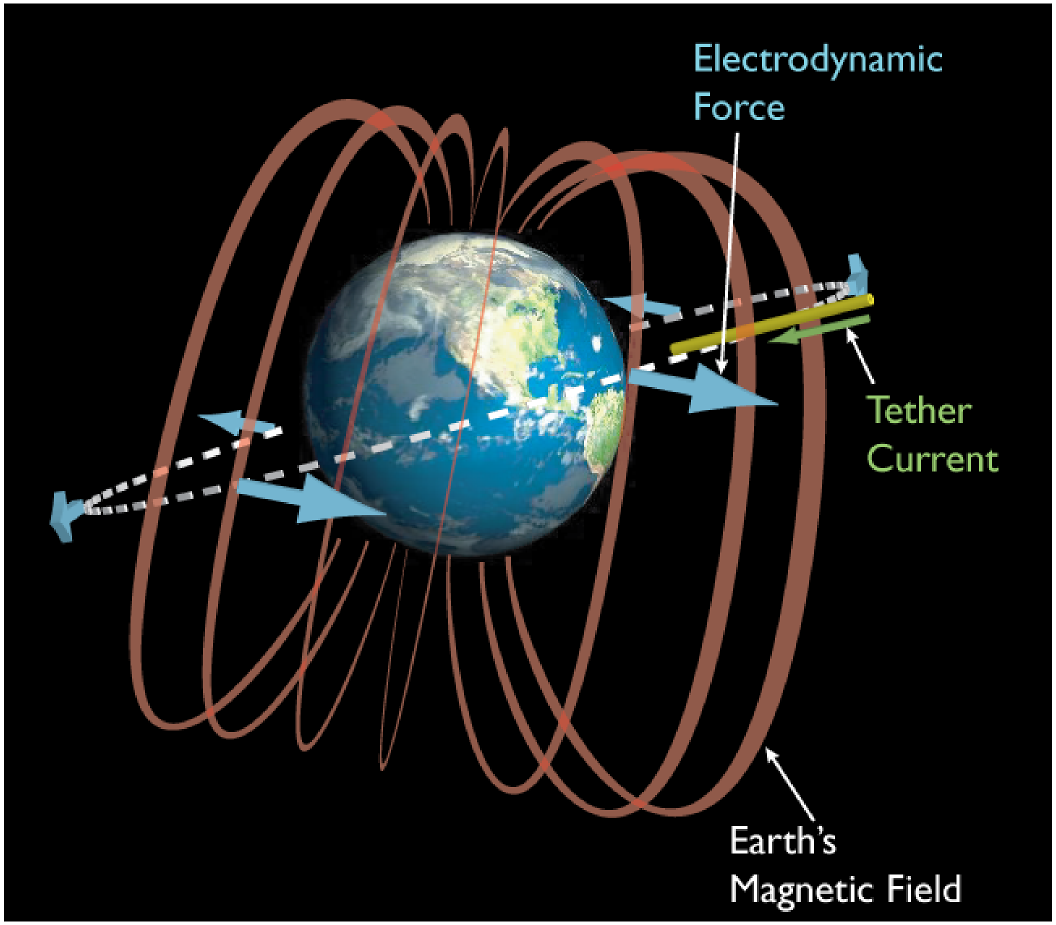
<u>EDTs provide</u>

- **high-thrust-to-power**
- **extremely high specific impulse performance**



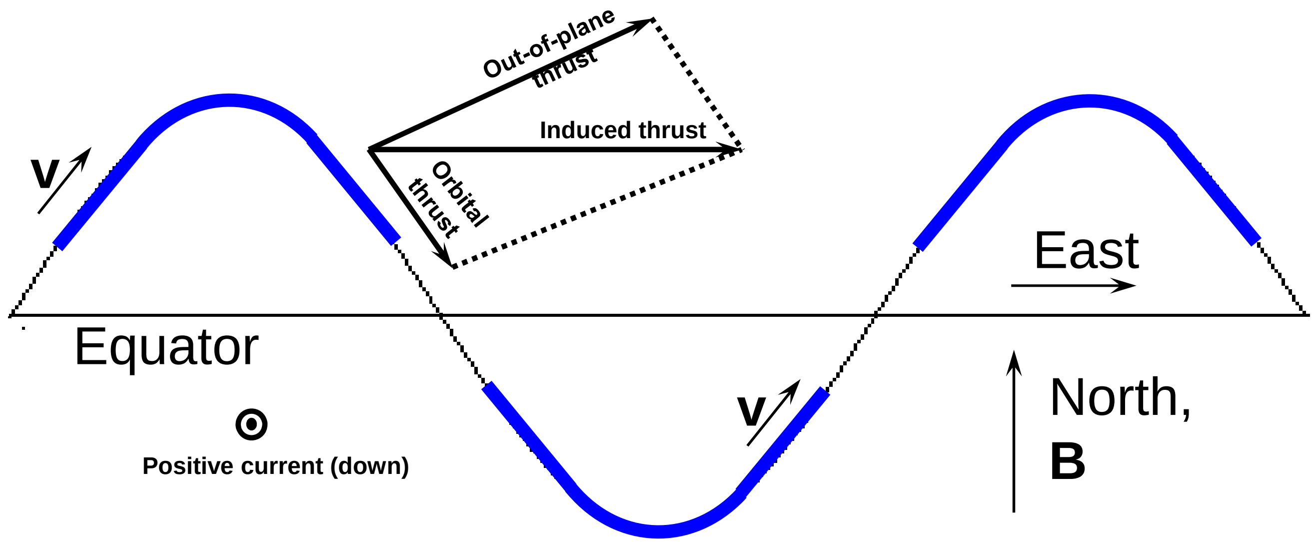
ED Tether Orbit Modification

- Over Orbit
  - B-field strength/direction varies
  - Plasma density varies
  - ED forces vary in magnitude and direction
- ED forces have components:
  - In-plane (orbit raising/lowering)
  - Out-of-plane (inclination change)
- Tether current can be modulated to change all six orbital elements



- Orbit raising/lowering best in low/moderate inclination orbits (<70°)
- Inclination change most effective in high inclination orbits
- Useful altitude range: ~300 km to ~2500 km
  - Potentially higher with ion emission technologies

Out-of-Plane Tether Thrust



The Out-of-plane Thrust Challenge

- ED tether force direction variable throughout orbit due to orientation change between tether and magnetic field vectors
- Can be thought of as tacking for “electrodynamic sailing”

Possible Solutions/Mitigations

- Confine reboost operations to non-equatorial regions of orbit
- Tether design naturally restores tether orientation against out-of-plane forces

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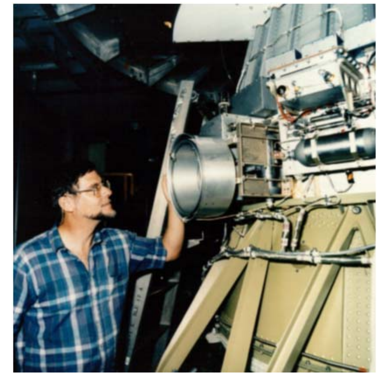
Selected Prior Tether Missions

- **Small Expendable Deployer System (SEDS) (1993-1994)**
  - SEDS 1: de-orbited small payload using 20 km tether
  - SEDS 2: controlled deployment of a 20 km tether
  - Plasma Motor Generator: ED physics using 500 m conducting wire, 2 HCPCs
- **Shuttle Tethered Satellite System (TSS) (1992, 1996)**
  - TSS-1: 200 m deployed, demonstrated stable dynamics
    - Last-minute S&MA demanded design change resulting in oversized bolt that jammed deployer (configuration control process failure)
  - TSS-1R: 19.9 km deployed, >5 hours of excellent data validating models of ED tether-ionosphere current flow
    - Arc caused tether to fail (tether fabrication/design/handling flaw)
    - No thrust measurements
- **TiPS - Survivability & Dynamics investigation (1996-2006)**
  - 4 km nonconducting tether, ~1000 km alt
  - Survived over 10 years on orbit
- **T-Rex – Bare Anode Tape Tether deployment (2010)**



Past missions demonstrated stable tether deployment & fundamental feasibility of electrodynamic propulsion.

Past missions did not measure ED thrust or demonstrate measurable orbit changes

Most tether missions HAVE been successful.
Mission failures were due to design process errors,
<u>not</u> due to fundamental physics.

TRL Snapshot

Dynamics

- **Ease of Deployment and Control (SEDS-1/2 & TSS-1)**
  - Deployment to 20 km, station keeping for more than 20 hrs, and satellite retrieval have been demonstrated
- **Short Tether Dynamic Stability (TSS-1)**
  - Gravity-gradient stabilization achieved at < 300 m.
- **Recovery from Dynamic Upsets & Slack Tether (TSS-1)**
  - Recover from significant dynamic perturbations, slack tether and satellite pendulous motions.
- **Retrieval (TSS-1)**
  - Nominal short distance retrieval from 276 m (most critical aspect).

Electrodynamics and Hardware Flight Validation

- Current collection in space 2-3 times more effective than predicted (TSS-1R)
  - Greater efficiency obtained w/gas emissions. Pre-TSS theoretical models much too conservative.
- Energy conversion from spacecraft orbit into electrical power demonstrated (TSS-1R)
  - A peak power of > 3.5 kW was generated.
- Bi-directional operations (PMG)
  - Polarity and current flow reversal demonstrated.
- Tether Survivability Demonstrated In-Space (TiPS)
  - TiPS tether (2 mm x 4 km) remained intact for more than **10 years** in a high-debris 1000-km orbit.
- Deployer Validation (6 missions)
  - Successful deployments with simple spool deployer (SEDS-1 & 2, PMG, TiPS) and reel deployer (TSS).

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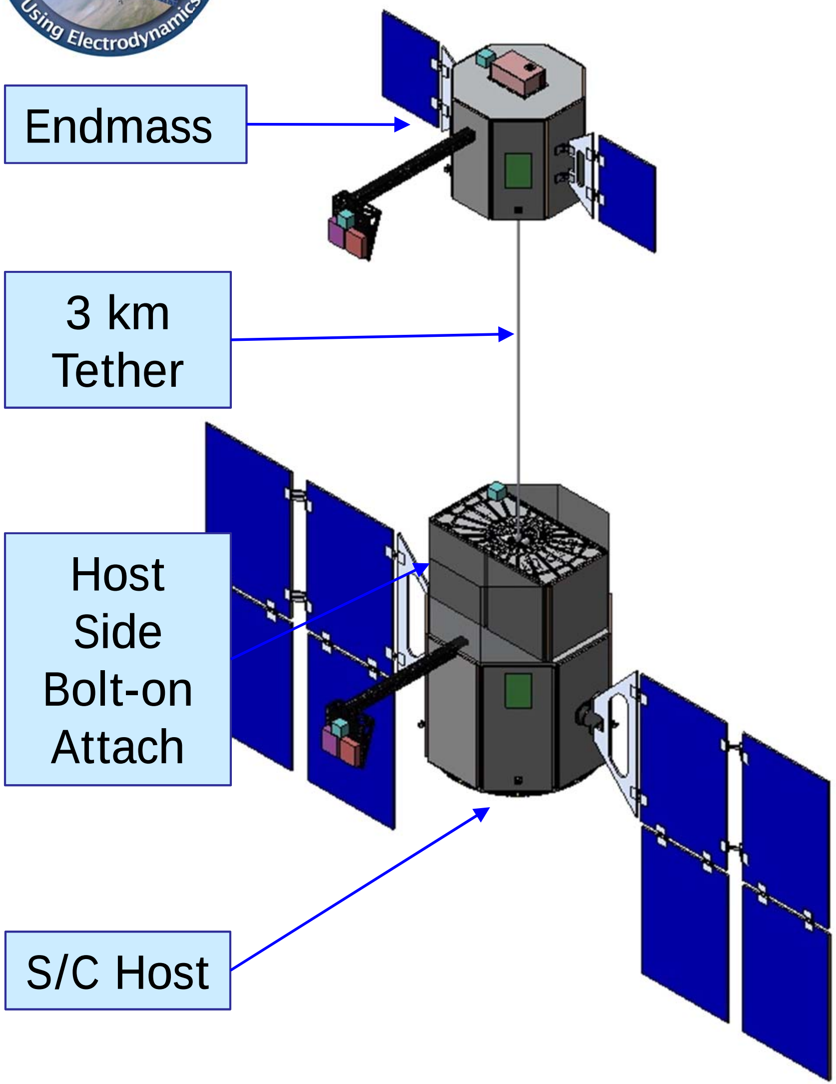
PROPEL MISSION GOALS

- **Demonstrate capability of ED tether technology to provide robust and safe, near-propellantless propulsion for orbit-raising, de-orbit, plane change, and station keeping, as well as perform orbital power harvesting and formation flight**

- **Fully characterize and validate the performance of an integrated ED tether propulsion system, qualifying it for infusion into future multiple satellite platforms and missions with minimum modification.**

PROPEL Configuration Driven By Goals



- **Need for Bi-polar current flow**
  - Fully insulated conducting tether
  - Hollow Cathode Plasma Contactors (HCPCs) at each end as baseline
  - Plasma sensors at each end for
    - HCPC performance
    - End-Body-to-Ionosphere connection
- **Tether retraction capability at *both* ends for confidence of safety**
- **Bolt-on architecture to Host S/C**

PROPEL Delivers a Space Flight Demonstration of Electrodynamic Tether Propulsion for Rapid Infusion into Future Missions

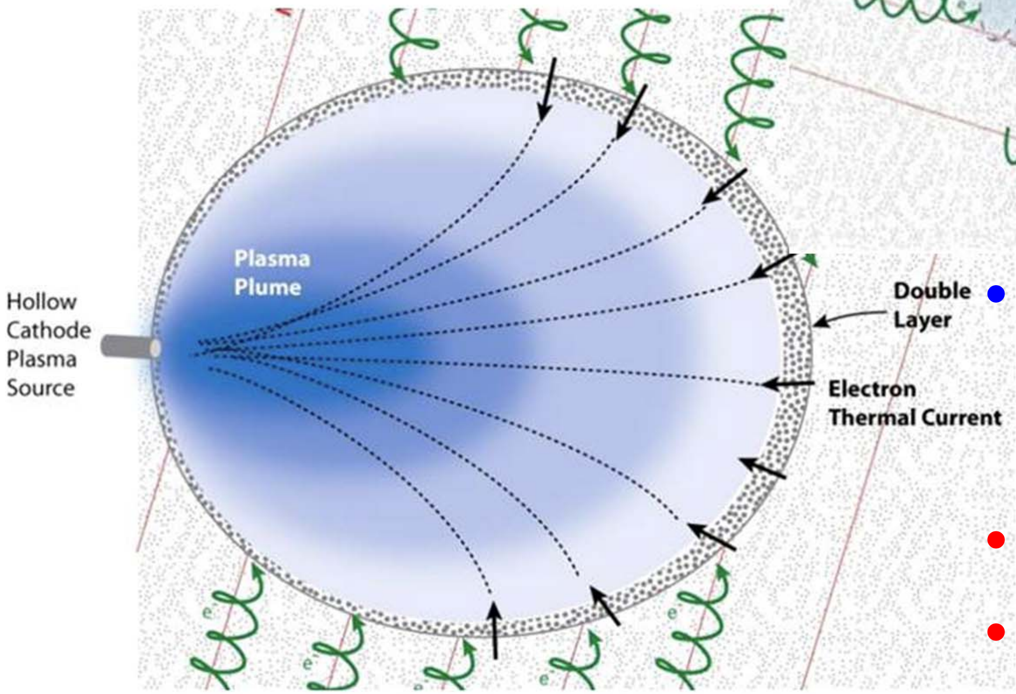
EDT Questions Driving Mission Design (1)

- What is predictable performance of hollow-cathode plasma contactor (HCPC) to collect current from and emit current to surrounding ionosphere in terms of:
  - tether current,
  - HCPC parameters, and
  - ionospheric conditions?
- How does ED tether performance change with increasing current (above 1 A)? How can the tether system be optimized for high current operation?
- What level of forecasting, real-time observation, performance prediction, and integrated simulation are required to enable <u>safe</u> ED tether system maneuvering?

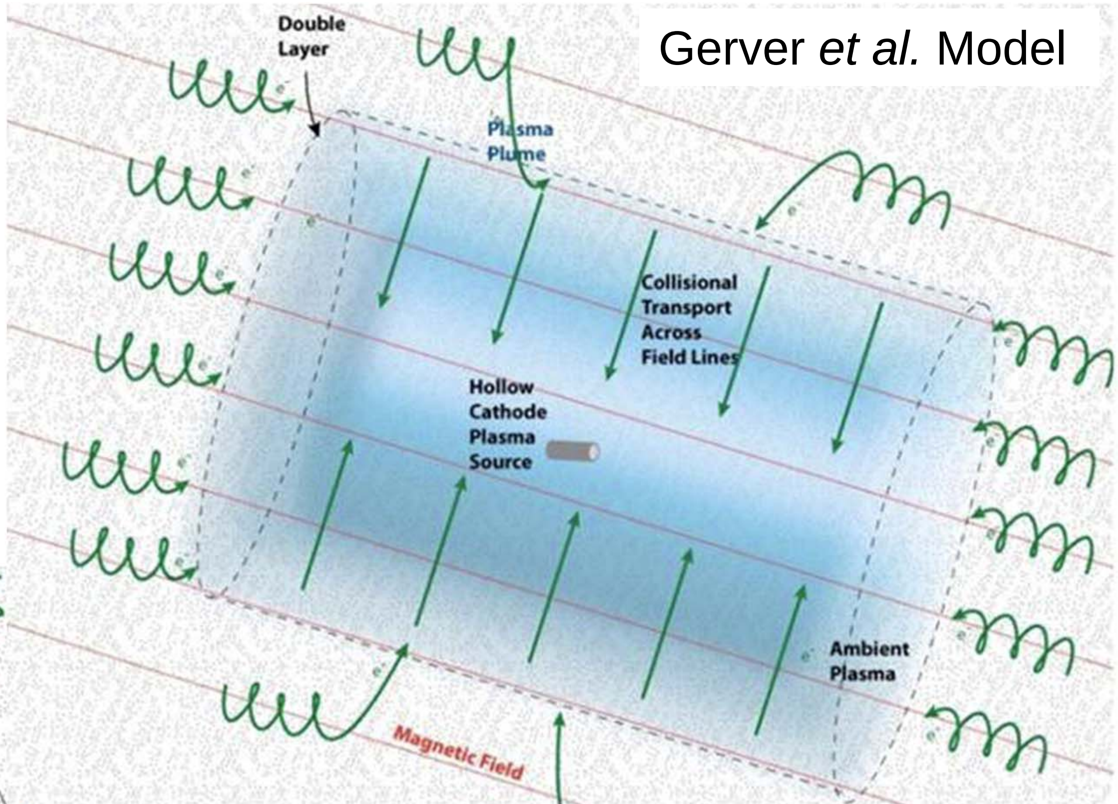
Plasma Emitter Contacting

- Tether current must = collected current
- Current continuity holds

Katz *et al.* (EWB) Model



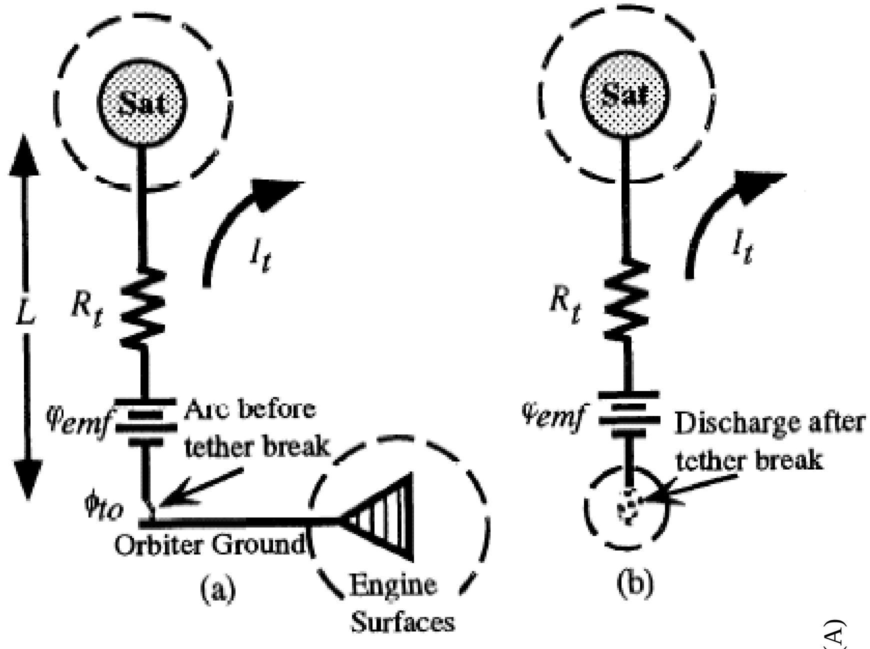
Gerver *et al.* Model



- Gerver *et al.* suggests higher electron currents are possible.
- Which model is right?
- Behavior as current goes up?

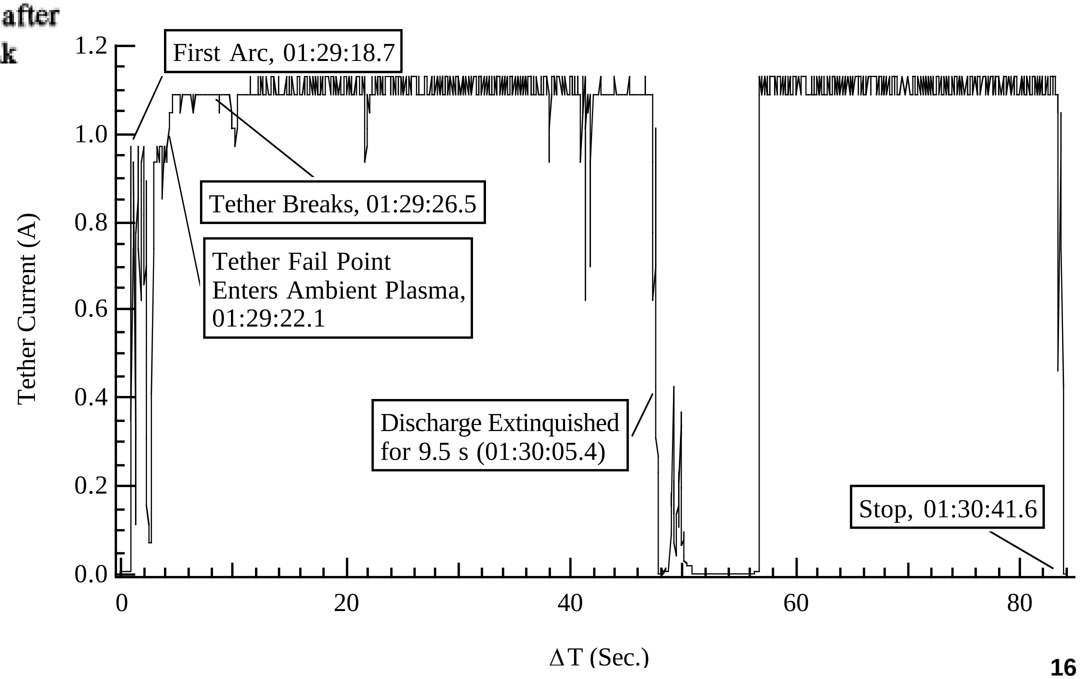
~1 A Currents During TSS-1R

$$V_{emf} = V_{sat} + I_t \cdot R_t \cdot L + V_{to} - V_{cathode}$$

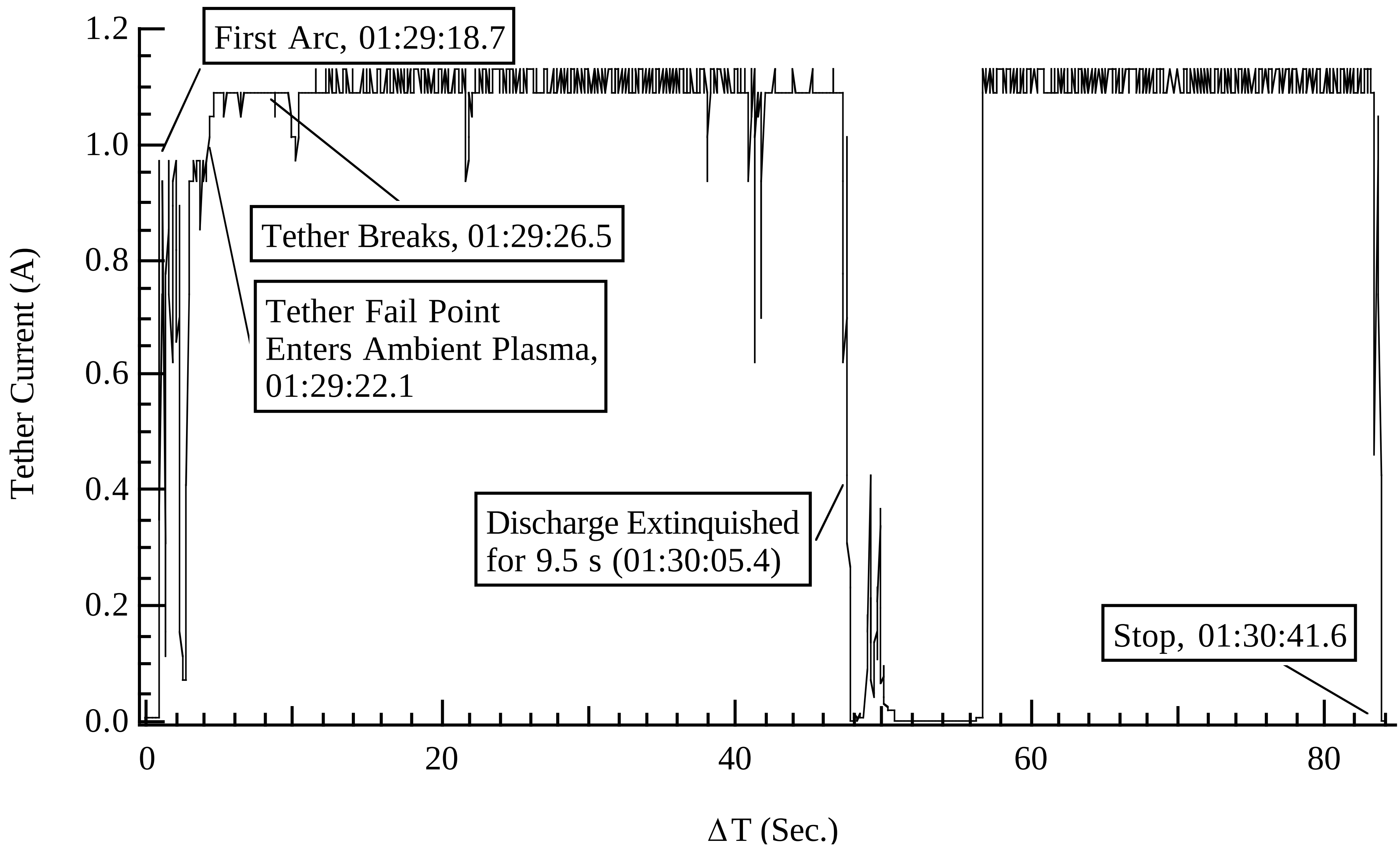


- **Dramatic increase in tether current shorted to Orbiter**
- **Larger current when in "contact" with Ionosphere**
- **Tether current limited by tether resistance**
- **What is ultimate limit for electron emission?**

- Laboratory demonstration verified ability to support discharge via
  - Trapped gas
  - Teflon ablation

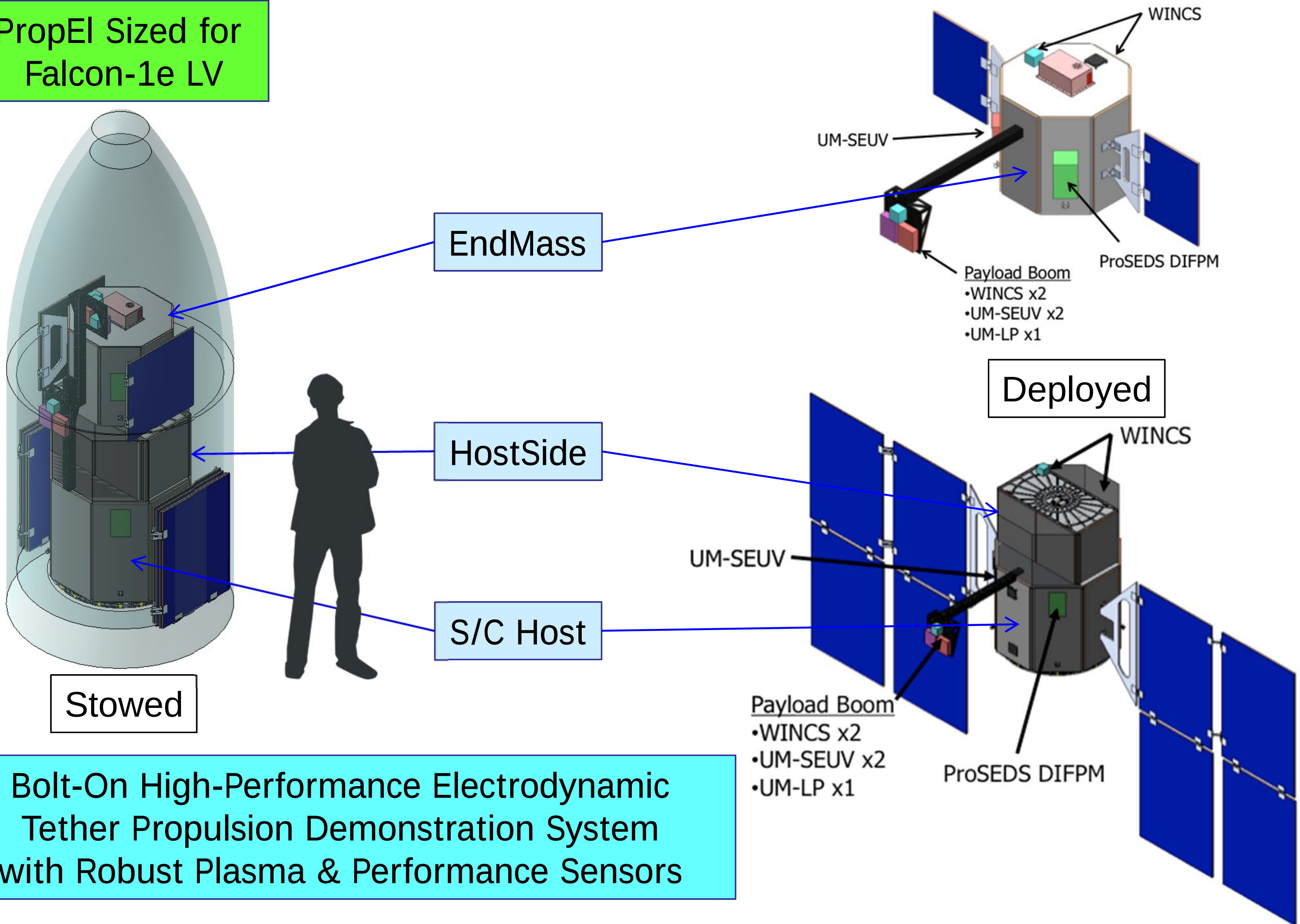


~1 A Currents During TSS-1R



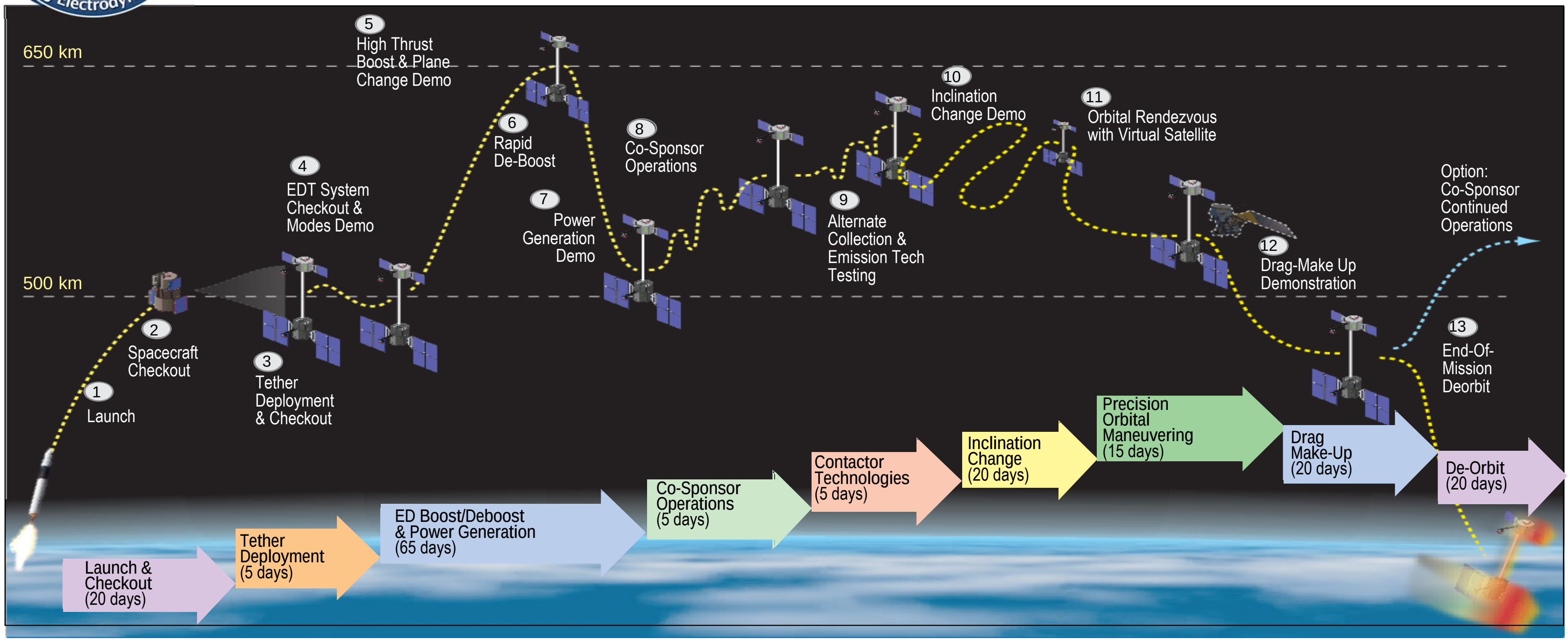
PropEl Baseline Configuration

PropEl Sized for Falcon-1e LV



Bolt-On High-Performance Electrodynamic Tether Propulsion Demonstration System with Robust Plasma & Performance Sensors

PROPEL Mission Overview



Mission Event Description			
1	Rideshare launch on a Falcon 9 to 500 km	8	Dedicated co-sponsor operations (restricted)
2	Host and End Mass checkout prior to separation and tether deployment	9	Alternate collector/emitter demos (SEP & EFED; zero propellant ΔV)
3	Controlled 3-km tether release and deployment	10	Inclination change demonstration (> 0.1 deg)
4	Diagnostics on ED tether and plasma environment, SV attitude control	11	Autonomous trajectory profiling and rendezvous (<10 km)
5	Orbit raising (>100 km; max ΔV characterization)	12	Orbit maintenance in high drag environment (<300 km)
6 & 7	Orbit lowering (>100 km) and power generator mode (>250 W)	13	Final de-orbit or transfer to co-sponsor for continued ops

PROPEL mission demonstrates all critical aspects of ED tether propulsion including orbit raising/lower, power generation, inclination changes, and de-orbit.

PROPEl Plasma Instrumentation

PropEl Plasma Instruments Fully Characterize EDT Propulsion System Interactions with Local Plasma & Field Conditions

PropEl Plasma & Field Instrumentation

Measurement	Instrument Heritage	Mounting Requirements				Physical Parameters				Notes
		Position	Attitude	Host	Endmass	Mass (kg)	Envelope (cm)	Power (W)	Data Rate (kb/s)	
Surface-Mounted										
Ion Distribution	UM-SEUV	Side	Normal to Surface	X	X	0.6	15x13x5	1	2	n_i, $E(n_i)$
"	ProSEDS DIFPM	Side	Normal to Surface	X	X	2.5	25x15x15	9	1.5	$\mathbf{v}_i(v_x,v_y,v_z)$, $n_i(\mathbf{v}_i)$, $E_i(\mathbf{v}_i)$
End-Body Potential	-	-	-	X	X	-	-	-	-	ϕ_f, use SEUV=DIFP+IDTS, or EDTS
Hollow Cathode Plume	Langmuir Probe	Near HC	Normal to Surface	X	X	0.6	15x13x5	1, (3.8*)	2	n_e, $E(n_e)$, ϕ_f, * cleaning power
Boom-Mounted										
Ion Distribution	UM-SEUV	Tip Bracket	in/out #	X		0.6*	14.6x12.9x4.6 *	1*	2*	n_i, $E(n_i)$, *(x2), # radially in/out wrt s/c
"	UM-LP	Tip Bracket	out	X		0.6	15x13x5	1, (3.8*)	2	n_e, $E(n_e)$, ϕ_f, * cleaning power
End-Body Potential	-			X						ϕ_f Measured/w ESA, SESA, or LP

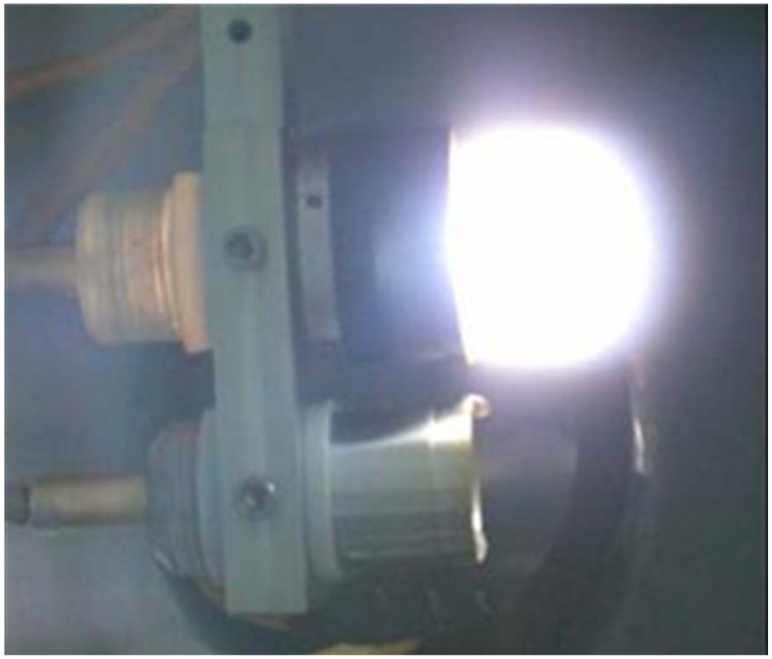
Outline

- **Electrodynamic (ED) Tether Propulsion Basics**
- **ED Tether TRL**
- **PROPEL & Design**
  - Mission Goals
  - Current Collection/Emission
  - Configuration
- **Possible future electron emitter/collector technologies**

Solid Expellant (SOLEX) Plasma Generator

- SOLEX Uses
  - Vaporization of proprietary hydrocarbon material (no corrosive vapors)
  - Self-Sustained discharge
- Stable to several amps
- Reliable restart

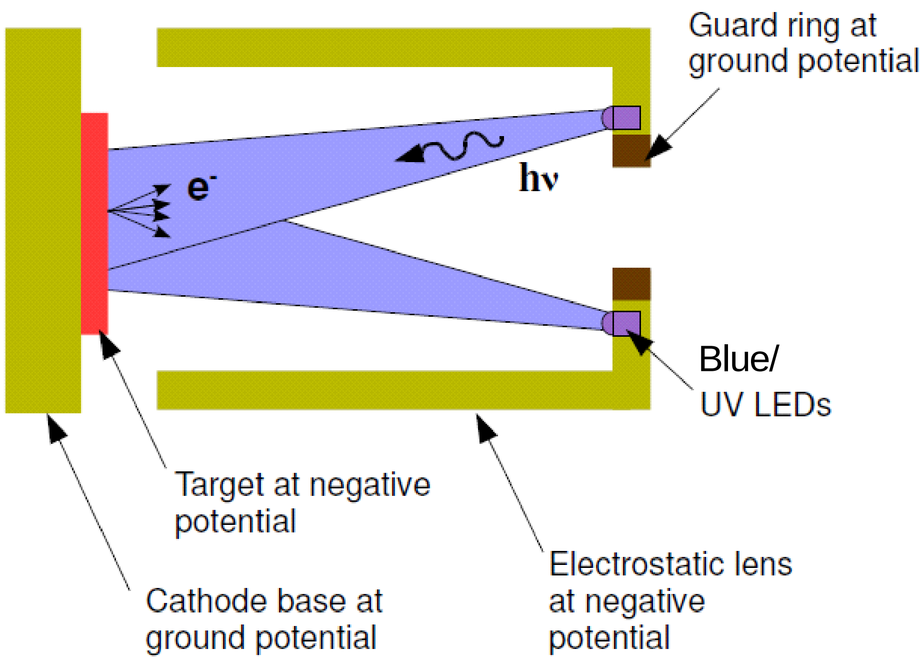
SOLEX Tested @ 1.8A



Nobie Stone, ManTech/Nexolve

Alternate Electron Emission Technologies

Photoeletron Electron Beam Generator (PEBG)



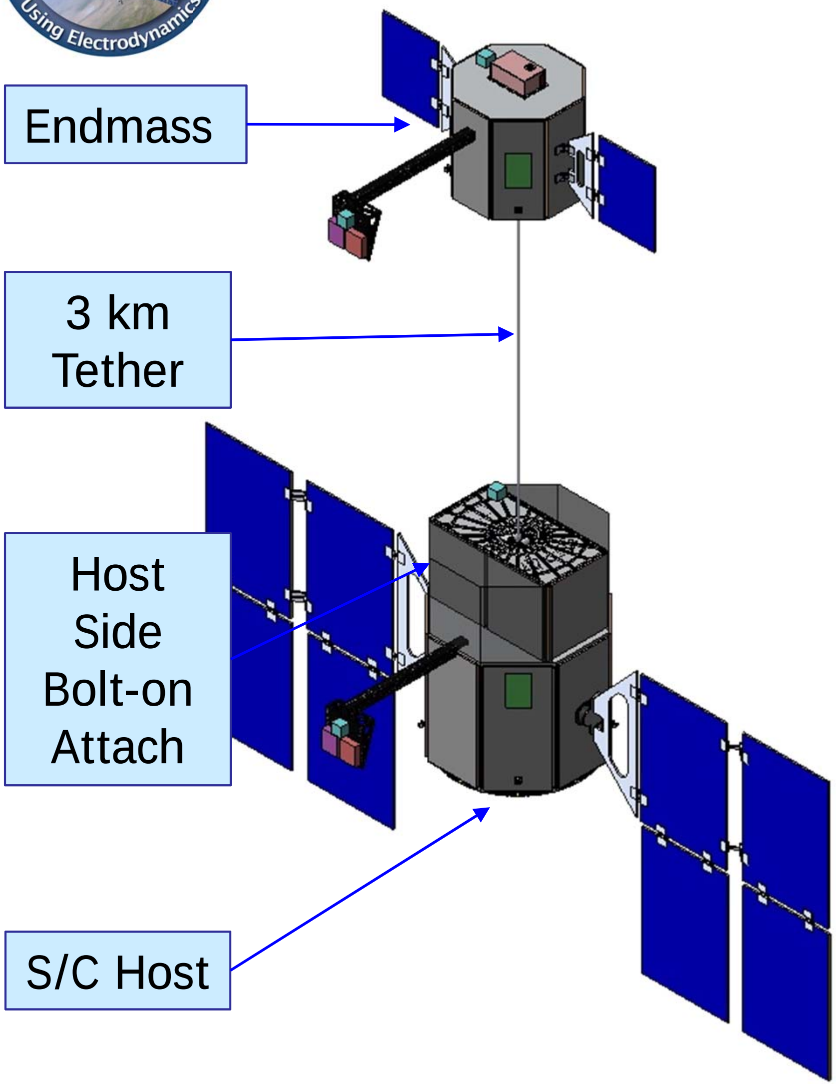
Linda Krause, NASA MSFC

- Uses high efficient blue/UV LEDs
- Target 1A for 12 LED's

Cold Cathode Electron Emission

- Advanced Spindt-style FEAs (Spindt, 2008)
  - Surface treatment
  - Arc protection
- Carbon Nanotube FEAs (Y. Okawa, 2007)
- Ion Proportional Emission Cathode (IProSEC) (Wheelock *et al.*, 2008)
- Calcium Aluminate Electride (C12A7), 0.6 eV Work Function material (Williams *et al.*, 2012)

Summary - PROPEL



PropEl would demonstrate robust and safe electrodynamic tether propulsion in Low Earth Orbit to enable multiple Space Science, Exploration and Space Utilization Missions for a variety of users

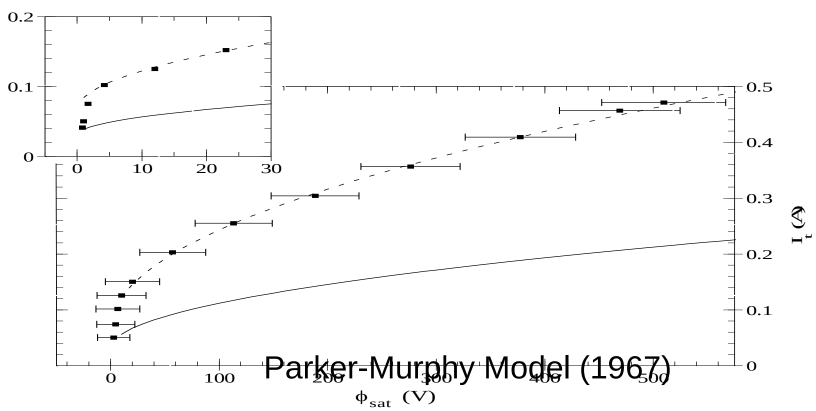
- LEO propulsion and station-keeping without the use of fuel
- Multipoint *in situ* LEO plasma measurements
- Enabling technology for more ambitious reusable tether upper stages
- Critical evaluation for future MW power generation and propulsion at Gas Giants

PropEl Delivers a Space Flight Demonstration of Electrodynamic Tether Propulsion for Rapid Infusion into Future Missions

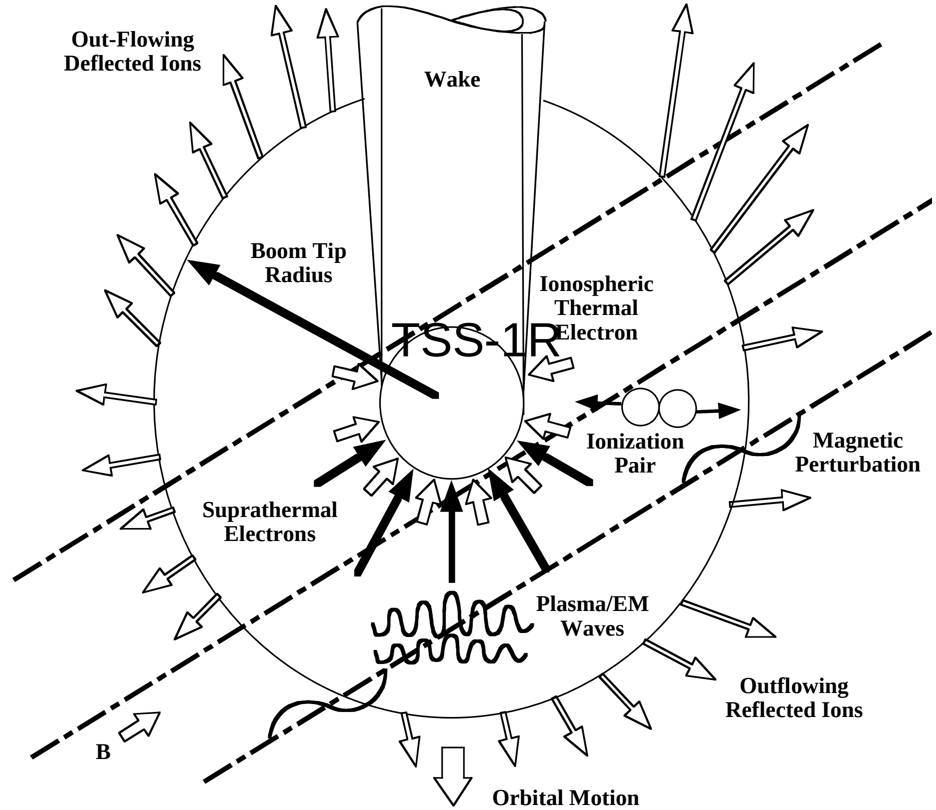
Backup

TSS–1R Enhanced Current Collection

TSS–1R Satellite



Parker-Murphy Model (1967)



N. Stone (1998)

Valuable practical information about ED Tethers learned from TSS-1R mission

EDT Flight Heritage (1/3)

1992	**TSS-1**	ED/Plasma Physics	• 20-km insulated conducting tether to study plasma-electrodynamic processes and tether orbital dynamics	– Tether deployment stopped after only 0.260 km; deployer jammed due to the too-long bolt + Demonstrated stable dynamics of short tethered system + Controlled retrieval of tether
1993	**SEDS-1**	Momentum Exchange	• Deployed payload on 20-km nonconducting tether and released it into suborbital trajectory	+ Successful, stable deployment of tether + Demonstrated deorbit of payload
1993	**PMG**	ED	• 500-m insulated conducting tether • Hollow cathode contactors at both ends	+ Demonstrated ED boost and generator mode operation
1994	**SEDS-2**	Dynamics	• Deployed 20-km tether to study dynamics and survivability	+ Successful, controlled deployment of tether with minimal swing – Tether severed after 3 days in space
1995	**OEDIPUS-C**	ED/Plasma Physics	• Sounding rocket experiment • 1174-m conducting tether, spinning	+ Obtained data on plane and sheath waves in ionospheric plasma

EDT Flight Heritage (2/3)

1996	**TSS-1R**	ED/Plasma Physics	• 20-km insulated conducting tether to study plasma-electrodynamic processes and tether orbital dynamics	+ Electrodynamic performance exceeded existing theories + Demonstrated ampere-level current – Flaw in insulation allowed high-voltage arc to cut tether prior to full deployment
1996	**TiPS**	Dynamics	• Deployed 4-km nonconducting tether to study dynamics and survivability	+ Successful deployment + Tether survived over 10 years on orbit
1999	**ATEx**	Dynamics	• Tape tether deployed with pinch rollers	– Deployment method "pushing on a rope" resulted in unexpected dynamics – Deployed only 22 meters before experiment was terminated
2000	**Picosats 21/23**	Formation	• 2 picosats connected by 30-m tether	+ Demonstrated tethered formation flight
2001	**Picosats 7/8**	Formation	• 2 picosats connected by 30-m tether	+ Demonstrated tethered formation flight
2002	**MEPSI-1**	Formation	• 2 picosats linked by ~15-m tether deployed from Shuttle	+ Tethered formation flight
2006	**MEPSI-2**	Formation	• 2 picosats linked by 15-m tether deployed from Shuttle	+ Tethered formation flight of nanosats with propulsion and control wheels

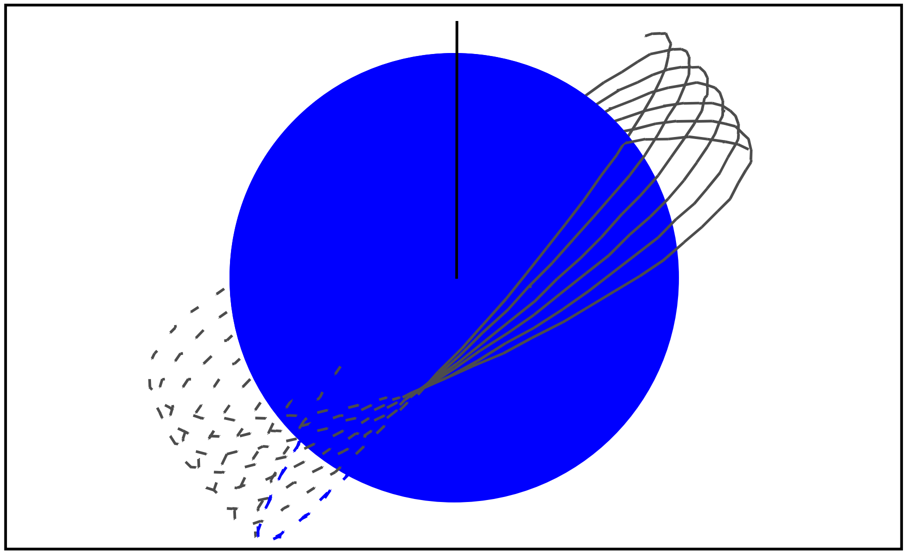
EDT Flight Heritage (3/3)

2007	**MAST**	Dynamics	• 3 tethered picosats to study tether survivability in orbital debris environment	– Satellite separation initiated but the actual length of the tether deployed is unknown
2007	**YES-2**	Momentum Exchange	• Deployed payload on 30-km nonconductive tether and released into suborbital trajectory	+ Tether deployed over 30 km – Re-entry capsule status is unknown.
2009	**AeroCube-3**	Formation	• Deployed from Minotaur on TacSat-3 launch a 2 picosats linked by 61-m tether	+ Tethered formation flight with tether reel and tether cutter
2010	**T-REX**	ED/Plasma Physics	• Sounding rocket experiment • 300-m bare tape tether	+ Tether deployed to 130-m

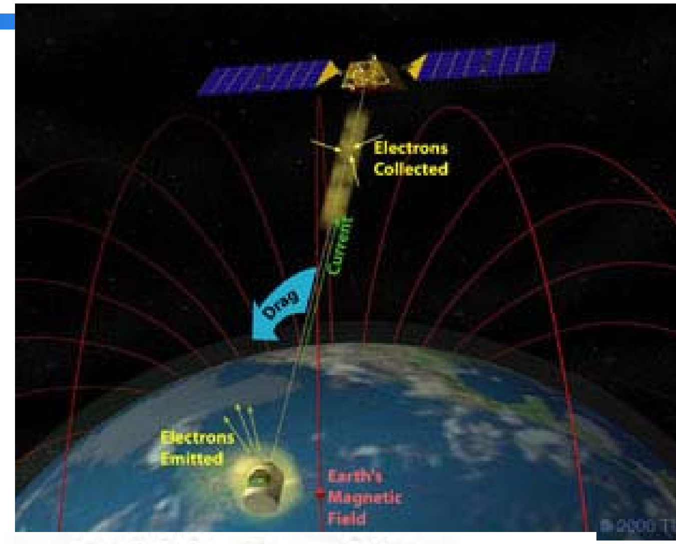
ED Tethers For Inclination and Altitude Change

Concept

- With an electrodynamic tether tug in LEO, satellites could be launched into another inclination and then "towed" to the proper inclination.
- LEO tether tug could also reboost or change multiple spacecrafts' orbital elements
- Important capability for high-value national assets.

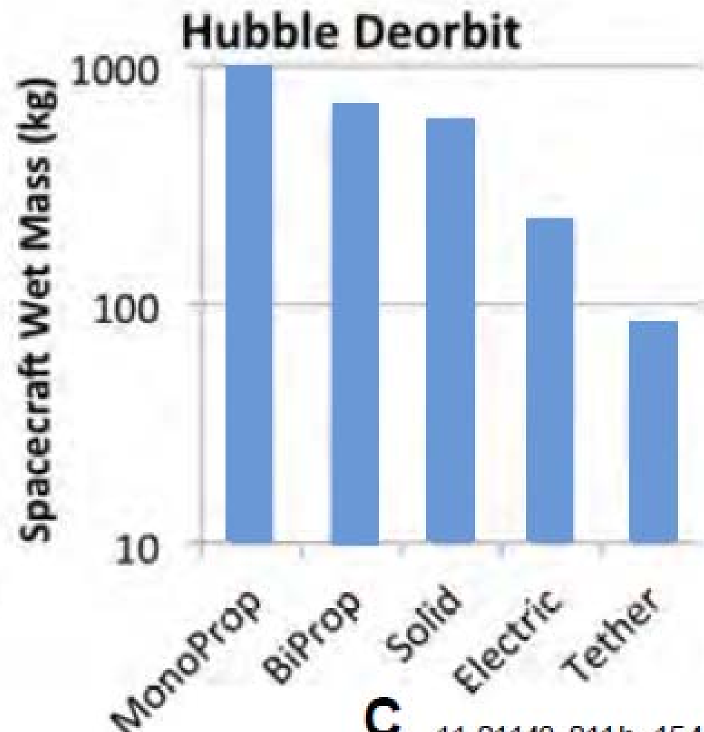


ED Tether Orbital Debris Mitigation



Concept

- Dead satellites can remain in orbit for extended periods of time and pose a debris and collision threat.
- An electrodynamic tether can be deployed from the spacecraft after it “dies” and will generate drag forces that will cause the spacecraft to deorbit.
- Unlike propulsive deorbit, the host spacecraft does not need to be operating or have attitude control—the tether generates the power and stability it needs.
- **Debris populations can be reduced significantly.**



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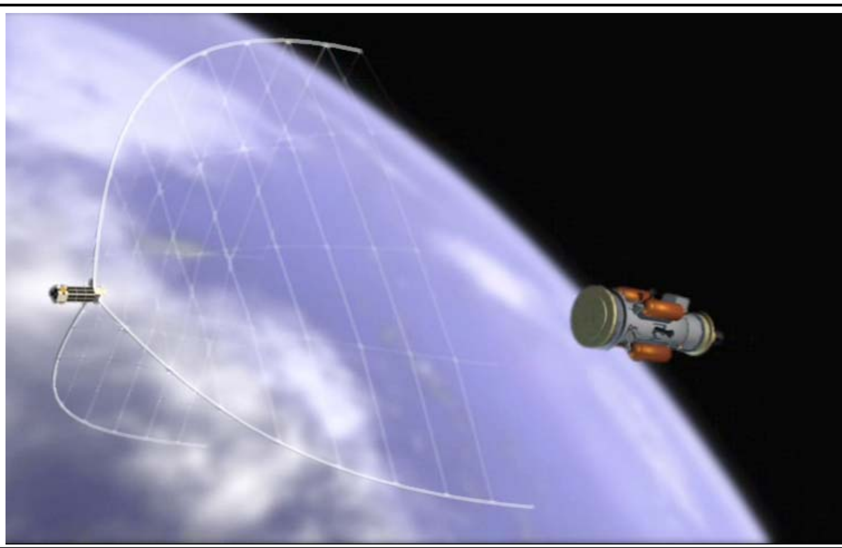
ED Tether Orbital Debris Remediation

Concept

- Electrodynamic Tether propelled vehicle performs rendezvous with large piece of orbital debris
- Vehicle attaches to the debris object using a net or harpoon
- Captured debris is maneuvered to low altitude and released for quick re-entry
- Tether vehicle boosts/maneuvers to the next debris object and repeats the process
- Can potentially remove tens of debris objects



Issues

- An EDT can provide the propulsion, but “something else” must:
  - Capture the target
  - Stabilize the target so the tether system can be attached safely
- Proximity operations with a librating tether
- Propulsion between 1000 km – 2000 km may take several months to perform (Under 1000 km weeks to months)
- Long life tethers need space flight validation

Tether System Instrumentation

EDT Tether System Performance Sensors:

Data Needed	Reason	Location	Sensors
Tether Tension	•Characterize tether dynamics •Sense slack tether, tension spikes, or other anomalous behavior	Host, Endmass	•Tensiometer •Optical fiber strain sensor integrated into tether
Spacecraft Attitude	•Characterize effects of tether dynamics on host S/C dynamics •Attitude control of S/C	Host, Endmass	•IMU •Magnetometer
Tether Voltage w.r.t. S/C	•Characterize EDT performance	Host, Endmass	•Voltmeter
Tether Current	•Characterize EDT tether performance	Host, Endmass	•Current sensor
Arc Sensing	•Detect and respond to tether arcing behavior	Host	•Voltmeter, high-frequency measurement capability
Endmass Position wrt Host	•Characterize & control EDT dynamics	Host, Endmass	•GPS •RelNav •LIDAR •Camera
Tether Configuration	•Characterize & control EDT dynamics	Host	•RelNav •Fiber Shape Sensor
Tether Integrity	•Detect tether break events	Host	•Fiber break sensor •Tether current/voltage sensors
Initial Deployment Dynamics	•Characterize tether and S/C behavior during deployment and operation	Host, Endmass	•Cameras •IMU •Accelerometer
Tether Deployer Operation	•Sensing and control of performance of tether deployer	Host, Endmass	•Optical Deployment Rate Sensor •Motor sensors (Hall, rotary encoders) •Thermistors

Tether Sensors Assess and Measure
EDT Operational Performance and State of Health